

NASA CR-170563

USER'S MANUAL
FOR
THERMAL ANALYSIS PROGRAM OF AXIALLY GROOVED HEAT PIPE
(HTGAP)

Prepared for
NASA Goddard Space Flight Center
Contract No. NAS5-24144
September, 1978



Prepared by
Yasuhiro Kamotani

Department of Mechanical and Aerospace Engineering
Case Western Reserve University

(NASA-CR-170563) USER'S MANUAL FOR THERMAL
ANALYSIS PROGRAM OF AXIALLY GROOVED HEAT
PIPE (HTGAP) (Case Western Reserve Univ.)
64 p HC A04/MF A01 CSCI 20D

N83-33102

Unclass
13603

G3/34

TABLE OF CONTENTS

Page

1. INTRODUCTION .	
2. ANALYSIS	
2.1 Problem Statement	
2.2 Problem Formulation	
2.3 Modes of Heat Input and Removal	
2.4 Puddle Effect Treatment	
2.5 Met'od of Solution	
3. PROGRAM DESCRIPTION	
3.1 General	
3.2 Input Description	
3.3 Output Description	
3.4 Sample Case	
REFERENCES	
NOMENCLATURE	
TABLES	
FIGURES	
APPENDIX A - PROGRAM FLOWCHART	
APPENDIX B - PROGRAM LISTING	
APPENDIX C - SAMPLE OUTPUT	

FORWARD

The computer program HTGAP described in this user's manual was prepared under NASA Contract NAS5-24144, "Axially Grooved Heat Pipe". The contract was administered by Goddard Space Flight Center, Greenbelt, Maryland, with Mr. Stanford Olendorf serving as technical monitor.

Dr. Y. Kamotani was responsible for the development of the analytical model and computer program.

1. INTRODUCTION

HTGAP is a computer program that numerically predicts the steady state temperature distribution inside an axially grooved heat pipe wall for a given groove geometry and working fluid under various heat input and output modes. The program computes both evaporation^{DP} and condenser film coefficients. The program is able to handle both axisymmetric and non-axisymmetric heat transfer cases. Non-axisymmetric heat transfer results either from non-uniform input at the evaporator or non-uniform heat removal from the condenser, or from both. The presence of a liquid pool in the condenser region under one-g condition also causes non-axisymmetric heat transfer, and its effect on the pipe wall temperature distribution is included in the present program.

The hydrodynamic aspect of an axially grooved heat pipe is studied in the Groove Analysis Program (GAP). The present thermal analysis program assumes that the GAP program (or other similar programs) is run first so that the heat transport limit and optimum fluid charge of the heat pipe are known a priori. The performance of an under-charged heat pipe is not considered in the present program.

2. ANALYSIS

2.1 Problem Statement

Figure 1 shows a typical axially grooved heat pipe. Each groove is designed to operate as an isolated liquid passage. Under steady state

conditions the rates of condensation and evaporation must be equal for each groove. For uniform heating at the evaporator and uniform cooling at the condenser (axisymmetric case) all the grooves are subject to identical boundary conditions so that the performance of the heat pipe can be deduced from the behavior of any one groove (assuming no excess liquid). For non-uniform heating and cooling, however, the rates of condensation and evaporation of a groove may be different from those of other grooves so that it is necessary to study the behaviors of all the grooves in order to predict the performance of the heat pipe.

The pipe wall temperature distribution is governed by a steady state heat conduction equation together with the exterior boundary condition (i.e., the way heat is applied to the evaporator and removed from the condenser) and the interior boundary condition (i.e., the rates of evaporation and condensation). Using cylindrical coordinates (Fig. 1) the governing equation is written as

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \frac{\partial T}{\partial r} + \frac{1}{r^2} \frac{\partial^2 T}{\partial \psi^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (1)$$

The boundary condition describing the thermal interaction between the groove and the liquid in it, and between the liquid and the vapor is very complicated because of the complex geometry of the groove. To avoid an unnecessary complicated solution in the present analysis, the inner surface thermal behavior is modelled as that shown in Fig. 2. An equivalent heat transfer coefficient ($h_{eg,e}$ or $h_{eg,c}$) is used to describe the thermal interaction between a hypothetical inner surface (radius R_i) and the vapor. This approach was initially used by Schneider and Yovanovich [1]. The computations of $h_{eg,e}$ and $h_{eg,c}$ are explained in the

following section. The region covered by a liquid pool is assumed to be thermally insulated.

The exterior boundary condition is determined by a specified (by the user) heater-cooler combination. Three different boundary conditions can be specified in the regions covered by the heater and cooler as explained in section 2.3. The rest of the pipe wall surface is assumed to be thermally insulated, or the user can specify parasitic heat loss or gain. The heat conduction through the pipe end caps is neglected in the present analysis.

Equation (1) together with the above mentioned boundary conditions is solved numerically using the successive-over-relaxation method.

2.2 Problem Formulation

To solve Eq. (1) numerically the heat pipe wall is divided into a number nodes as shown in Fig. 3. The cylindrical wall is divided into L nodes radially (r-direction), M nodes (equal to the number of grooves) circumferentially (ψ -direction), and N nodes axially (z-direction). An energy balance applied to every node yields a system of finite difference equations representing the heat conduction equation (1). The following finite difference formulation follows Schneider and Yovanovich [1].

For the (i,j,k) th node the finite difference equation is written as

$$\begin{aligned} C_5 T_{i,j,k} = & C_1 T_{i-1,j,k} + C_2 T_{i+1,j,k} \\ & + C_3 T_{i,j-1,k} + C_4 T_{i,j+1,k} \\ & + C_5 T_{i,j,k-1} + C_6 T_{i,j,k+1} \end{aligned} \quad (2)$$

where

$$\begin{aligned} C_{1,2} &= \frac{k_w (r_i \mp \sigma r^\mp / 2) \Delta \psi \Delta Z}{\sigma r^\mp} \\ C_{3,4} &= \frac{k_w \Delta Z}{\sigma \psi^\mp} \ln \left[\frac{r_i + \sigma r^+ / 2}{r_i - \sigma r^- / 2} \right] \\ C_{5,6} &= \frac{k_w \Delta \psi}{\sigma Z^\mp} \left[\frac{(r_i + \sigma r^+ / 2)^2 - (r_i - \sigma r^- / 2)^2}{2} \right] \end{aligned} \quad (3)$$

The heat transfer rate at the hypothetical inner surface (Fig. 2) of the pipe wall is determined by the equivalent heat transfer coefficient h_{eq} . h_{eq} represents the total thermal conductance between the pipe inner surface (radius R_i) and the vapor. Then, the interior boundary condition is incorporated into the above formulation by putting

$$C_1 = - \frac{\frac{h_{eq}}{k_w} \frac{\Delta r}{2}}{1 + \frac{h_{eq}}{k_w} \frac{\Delta r}{2}}$$

$$T_{i-l,j,k} = T_v \quad (4)$$

for those nodes contacting the vapor. In the present analysis the vapor region is modeled as one node with a uniform temperature T_v .

If the pipe inner surface temperature is lower than T_v , condensation takes place. In Ref. 2 Kamotani suggested a numerical method to compute the condenser film coefficient of a grooved heat pipe. However, the method is too complex to be included in the present program. After some calculations using the method under various conditions, it was found that the following expression for the equivalent heat transfer coefficient expresses well the computed as well as experimental values.

$$h_{eg,c} = \frac{N k_L}{2\pi R_i} \frac{1}{.02 + \frac{k_L}{k_w} \frac{D}{S}} \quad (5)$$

If the pipe inner surface temperature is larger than T_v , evaporation takes place. After studying several experimental and analytical investigations on the evaporator film coefficient of a grooved heat pipe (Ref. 3 - 7), the following expression for the equivalent heat transfer coefficient is suggested.

$$h_{eg,e} = \frac{N k_L}{2\pi R_i} \frac{1}{.07 + \frac{k_L}{k_w} \frac{D}{S}} \quad (6)$$

The boundary condition at the exterior surface of the heat pipe is discussed in the following section.

2.3 Modes of Heat Input and Removal

The exterior boundary condition is determined by the way heat is applied to the evaporator and removed from the condenser. Three typical boundary conditions are considered in the present analysis. They are shown schematically in Fig. 4, and discussed below.

Type 1 Boundary Condition

Total heat flux Q and vapor temperature T_v are given. This boundary condition is incorporated into Eq. (2) by adding a source (or sink) term

$$S = \pm q R_{ovT} \Delta \psi \Delta Z$$

to the right hand side of Eq. (2) for those nodes contacting the heater or cooler. q is heat flux per unit area (Q divided by heating or cooling

area). + sign is for heat input, and - sign for heat removal.

Type 2 Boundary Condition

Total heat flux Q at the evaporator and condenser surface temperature $T_{w,c}$ are given. For those nodes contacting the heater the treatment is the same as above. The surface temperatures of those nodes contacting the cooler are set equal to $T_{w,c}$. The vapor temperature is computed from the relation

$$\sum_{\text{inner surface}} h_{eg} (T_{s_i} - T_v) = 0$$

where T_{s_i} is the inner surface temperature.

Type 3 Boundary Condition

Both evaporator and condenser surface temperatures $T_{w,e}$ and $T_{w,c}$ are given. The specification of this boundary condition and the computation of T_v are the same as above.

If there is parasitic heat loss or gain from the heat pipe to the environment, it is accounted for by putting

$$C_2 = \frac{\frac{h_{par} \Delta t}{R_w}}{1 + \frac{h_{par} \Delta t}{R_w}}$$

$$T_{i+1,j,k} = T_{amb}$$

for the nodes on the pipe outside surface. h_{par} is the heat transfer coefficient between the pipe and the environment, and T_{amb} is the ambient temperature.

2.4 Puddle Effect Treatment

At the user's option the program investigates the effect of a liquid pool on the pipe wall temperature distribution in one-g and under an over-charged condition. The excess liquid forms a liquid pool at the bottom of the heat pipe, which influences the pipe performance (puddle effect). The hydrodynamic aspect of the puddle flow is studied in GAP. The present program considers mainly the thermal aspect.

The free surface of the liquid pool is assumed to be flat in the present analysis. The assumption is not valid when the heat pipe is operating at a small tilt angle under a high heat load, or when the ratio $\rho_l g R_v^2 / \sigma$ (Bond number) is on the order of one or less. Therefore to avoid a complex combined hydrodynamic and thermal analysis, the puddle effect at zero tilt angle is not considered in the present program.

Depending on a given tilt angle and amount of excess fluid, the puddle shape is classified into one of four shapes depicted in Fig. 5. To simplify the numerical analysis the following approximate relation between the puddle volume and the puddle depth H_1 at the condenser end is used,

$$VOL = \frac{\pi}{\tan \alpha} R_v^3 \left(\frac{H_1}{2 R_v} \right)^2$$

The pipe inner surface submerged in the pool is assumed to be thermally insulated. Numerically C_1 is set equal to zero for the submerged nodes on the pipe inner surface. At a given z location the submerged region is specified by the angle θ (Fig. 5). The angle θ is related to the puddle depth H by the equation

$$\theta = \cos^{-1} \left(1 - \frac{H}{R_v} \right)$$

2.5 Method of Solution

A set of finite difference equations (2) together with the aforementioned boundary conditions are solved by successive-over-relation to determine the pipe wall temperature distribution. Recognizing the fact that the heat transfer in the pipe wall is predominantly in the radial direction, the temperature distribution in the r-direction is determined first to reduce the convergence time (Schneider and Yovanovich [1]), that is, at a given (ψ, z) location, L equations in the r-direction are solved simultaneously.

Once the temperature distribution in the pipe wall is determined, the program computes the evaporator and condenser over-all film coefficients which are defined as

$$h_e = \frac{Q}{2\pi R_v L_e (\bar{T}_{w,e} - T_v)} \quad , \quad h_c = \frac{Q}{2\pi R_v L_c (T_v - \bar{T}_{w,c})} \quad (7)$$

Notice that the coefficients are based on the vapor core diameter ($2R_v$) and the difference between the vapor temperature and the average evaporator or condenser surface temperature.

The program also computes the heat load of each groove. In case of non-axisymmetric heat transfer each groove transports different amounts of heat so that all the grooves do not dry-out at the same time. The program checks whether the heat load of any of the grooves exceeds the heat transport limit of a single groove. To compute the single groove transport limit the user must specify the heat transport limit of the heat pipe in zero-g (or under zero tilt without the puddle effect) and under

ORIGINAL PAGE IS
OF POOR QUALITY

axisymmetric heat transfer conditions, which can be determined either from GAP or from similar hydrodynamic analyses. If the transport limit is not known, it can be set equal to an arbitrary large value, but in that case it is noted that the program does not predict partial dry-out condition. In zero-g or for horizontal operations without the puddle effect in one-g, the single groove transport limit is simply equal to the heat pipe transport limit divided by the total number of grooves. Under tilt conditions in one-g without the puddle effect the single groove transport limit is calculated as

$$g_{limit} = \frac{Q_{limit}}{N} \left(1 - \frac{ELV}{X_{ST}} \right) \quad (8)$$

In the above relation the static height of the pipe (X_{ST}) must be specified by the user. X_{ST} can be determined from GAP or from the relation

$$X_{ST} = \frac{2\sigma}{\rho_l g W_{min}}$$

When the puddle effect is included, the single groove transport limit is calculated as (Ref. 8)

$$g_{limit} = \frac{Q_{limit} L_{eff}}{N L'_{eff}} \left(1 - \frac{L'_{eff} \tan \alpha}{X_{ST}} \right) \quad (9)$$

where

$$L'_{eff} = \begin{cases} \frac{1}{2} L_e + L_a + \frac{1}{2} (L_p - L_c) & \text{if } L_p \leq L_c \\ \frac{1}{2} L_e + (L_p - L_c) & \text{if } L_c < L_p \leq L_c + L_a \\ \frac{1}{2} (L_p - L_a - L_c) & \text{if } L_p > L_c + L_a \end{cases}$$

If the heat load of any of the grooves exceeds the transport limit, the program writes-out a statement to inform the user about the partial dry-out condition.

It is noted that the above analysis is based on the assumption that there is a groove-to-groove liquid communication in the condenser section. According to Kamotani [9] such condition most likely prevails in one-g as well as in zero-g applications. Therefore the present program does not consider the situations where there is no liquid communication between the grooves.

3. PROGRAM DESCRIPTION

3.1 General

HTGAP's flow chart is given in Appendix A, and the program listing in Appendix B. The program is written in Fortran IV, and is designed to operate on the IBM 360 computer system. The field length of the program requires 60 K actual works, and the complications of the program requires typically .5 CPU minutes and .5 IO minutes. The CPU time varies depending mainly on the desired accuracy in the numerical iteration. The variables and constants used in HTGAP are listed at the beginning of the program. HTGAP uses metric units.

HTGAP consists of a main program and a subprogram. The main program reads the input data, conducts numerical iterations, and outputs the final results. If required, the subprogram (PUDDLE) is called, which determines the region covered by the puddle.

3.2 Input Description

The HTGAP user must correctly specify the properties of the working fluid and the pipe material, the pipe and groove geometry, the selection of the type of heat input and removal mode, and the operational mode of the program. The set-up of the input data deck is shown in Table 1. In case of multiple runs these input cards specified in Table 1 (also in the program) must be repeated for each additional run. The rest of the parameters remain fixed.

The physical properties of the working fluid and the pipe material should be evaluated at the vapor temperature (T_v) for type 1 boundary condition, and at $T_{w,c}$ for types 2 and 3 (T_v is not known a priori in these cases). In the latter cases a better accuracy is obtained by running the program twice, evaluating the physical properties at the calculated vapor temperature from the first run.

Care must be taken in specifying the heating and cooling zones. Four numbers are used to specify the circumferential extent of the heating (or cooling) zone. They are angles (in degrees) measured counter-clockwise from the pipe bottom. Some examples are shown in Fig. 6. If only two numbers are needed (examples 2 and 3), the rest of the numbers should be set equal to ^{or higher} an arbitrary number ~~larger~~ than 500.

3.3 Output Description

The program output from the illustrative example (explained in the following section) is shown in Appendix C. On the first output page the program outputs the input data consisting of the names of the working fluid

and the pipe material, the pipe and groove geometry and the heating and cooling mode. Those parameters are the same for all the cases in case of multiple runs. The following two pages describe the heat pipe operating conditions, the physical properties and the computational results for one run. The computational results include the heat pipe surface temperature distribution, the heat load of each groove and the pipe performance characteristics (average evaporator and condenser temperature drops, film coefficients, partial dry-out conditions, etc).

3.4 Sample Case

To illustrate HTGAP, the following case is studied. An axially grooved aluminum heat pipe filled with ammonia is operating at 250 K in one-g.

heat pipe geometry

evaporator length	$L_e = .3048 \text{ m}$
adiabatic length	$L_a = .4572 \text{ m}$
condenser length	$L_c = .1524 \text{ m}$
outer diameter	$2R_{out} = .159E-1 \text{ m}$
inner diameter	$2R_{in} = .1088 \text{ E-1 m}$
vapor core radius	$R_v = .45E-2 \text{ m}$

groove geometry

number of grooves	$N = 27$
groove depth	$D = .108E-2 \text{ m}$
average land width	$\bar{S} = .37E-3 \text{ m}$

heating and cooling mode

type 1 boundary condition. The heating region is the upper half of the pipe, and the cooling region is the lower half. No parasitic heat loss or gain is considered.

total heat transport	$Q = 80 \text{ W}$
vapor temperature	$T_v = 250 \text{ K}$

properties of working fluid and pipe material

fluid (ammonia) density	= 670 kg/m
fluid thermal conductivity	= .592 W/mK
aluminum thermal conductivity	= 180 W.mK

heat pipe operating conditions

one-g condition	
elevation	ELV = .6E-2 m
excess mass charge	XMASS = 1.2 g.

heat pipe performance limits

maximum heat transport (in zero-g)	$Q_{\text{limit}} = 215 \text{ W}$
static height	$X_{\text{ST}} = .14\text{E}-1 \text{ m}$

The sample input is given in Table 2. The program output for the above case is presented in Appendix C. The results show that the evaporator and condenser film coefficients are .67 and $1.03 \text{ W/cm}^2\text{K}$, respectively, and no partial dry-out is expected. 55 iterations are needed to obtain the temperature distribution within .01 K accuracy.

17.5 W/mK

REFERENCES

1. Schneider, G.E. and Yovanovich, M.M., "Three-Dimensional Thermal Analysis of High Capacity Heat Pipe with Circumferential V-grooves", final report to the Communications Research Center, Department of Communications, Ottawa, Ontario, 1974.
2. Kamotani, Y., "Analysis of Axially Grooved Heat Pipe Condensers", AIAA Progress in Astronautics and Aeronautics, Vol. 56, 1977.
3. Berger, M.E. and Feldman, K.T. Jr., "Analysis of Circumferentially Grooved Heat Pipe Evaporators", ASME Paper 73-WA/HT-13, 1973.
4. Schneider, G.E. and Yovanovich, M.M., "Thermal Analysis of Trapezoidal Grooved Heat Pipe Walls", report to the Communications Research Center, Department of Communications, Ottawa, Ontario, 1964.
5. Kamotani, Y., "Thermal Analysis of Axially Grooved Heat Pipes", Proc. of 2nd International Heat Pipe Conference, 1976.
6. Kamotani, Y., "Evaporator Film Coefficients of Grooved Heat Pipes", Proc. of 3rd International Heat Pipe Conference, 1978.
7. Schlitt, K.R., Kirkpatrick, J.P. and Brennan, P.J., "Parametric Performance of Extruded Axial Grooved Heat Pipes from 100 to 300 K", AIAA Progress in Astronautics and Aeronautics, Vol. 39, 1976.
8. B & K Engineering, "User's Manual for Groove Analysis Program (GAP)", report BK012-1007, 1976.
9. Kamotani, Y., "Effects of One-Sided Heat Input and Removal on Axially Grooved Heat Pipe Performance", AIAA Progress in Astronautics and Aeronautics, Vol. 60, 1978.

NOMENCLATURE

$C's$	finite difference coefficients
D	groove depth
ELV	elevation
g	gravitational acceleration
h	over-all film coefficient
h_{eq}	equivalent heat transfer coefficient
h_{par}	heat transfer coefficient for parasitic heat loss or gain
H	puddle depth
H_1	puddle depth at condenser end
k	thermal conductivity
L_a	length of adiabatic section
L_c	length of condenser section
L_e	length of evaporator section
L_p	puddle length
L_{eff}	effective transport length ($=L_a + 1/2 (L_e + L_c)$)
L'_{eff}	defined in Eq. 9
N	number of grooves
Q	total heat transport
q	heat flux per unit area
Q_{limit}	maximum heat transport
q_{limit}	single groove heat transport limit
R_i	pipe inner radius
R_{out}	pipe outer radius

R_v	vapor core radius
\bar{S}	average land width
T	temperature
T_{si}	inner surface temperature
T_v	vapor temperature
\bar{T}_w	average outside surface temperature
T_{amb}	ambient temperature
W_{min}	groove minimum width
X_{ST}	static height
X_{MASS}	excess mass charge
(r, ψ, z)	cylindrical coordinate system defined in Fig. 1
α	tilt angle
δ	spacing between two adjacent nodes
Δ	nodal width
γ 's	angles to specify heating and cooling zones
θ	puddle angle
ρ	density
σ	surface tension

Subscripts

c	condenser
e	evaporator
l	liquid
w	wall

TABLE 1 INPUT CARDS DESCRIPTION

<u>Card No.</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>	<u>Unit</u>	<u>Remarks</u>
1	3F10.4	XLE	evaporator length	m	
		XLAD	adiabatic length	m	
		XLC	condenser length	m	
2	I5 5E10.4	NGRV	no. of grooves	---	
		GDEPTH	groove depth	m	
		WIDTH	average land width	m	
		ROUT	pipe outer radius	m	
		RIN	pipe inner radius	m	
		RV	vapor core radius	m	
3	5A2 10A2	IFLUID	name of working fluid	---	
		JPIPE	name of pipe material	---	
4	3F10.5	Q	total heat transport	W	
		TV	vapor temperature	K	if
		QMAX	max. heat transport	W	KTYPE = 1
	3F10.5	Q	total heat transport	W	
		TCOND	condenser surface temp.	K	if
		QMAX	max. heat transport	W	KTYPE = 2
	3F10.5	TEVP	evaporator surface temp.	K	
		TCOND	condenser surface temp.	K	if
		QMAX	max. heat transport	W	KTYPE = 3
5	3E15.4	CONDL	liquid thermal conductivity	W/mK	
		RHO	liquid density	Kg/m ³	
		CONDW	pipe thermal conductivity	W/mK	
6	3E15.4	XSM	excess mass charge	Kg	Skip this card
		EL	elevation	m	if MGRVT = 1
		XST	static height	m	
7	4F10.3	PSIE(1)	angles to specify	DEG.	
		PSIE(2)	heating zone		
		PSIE(3)			
		PSIE(4)			

Table 1 Input Cards Description (cont'd)

<u>Card No.</u>	<u>Format</u>	<u>Name</u>	<u>Description</u>	<u>Unit</u>	<u>Remarks</u>
8	F10.3	PSIC(1)	angles to specify	DEG.	
		PSIC(2)	cooling zone		
		PSIC(3)			
		PSIC(4)			
9	F10.3	TEMPS	ambient temp.	$\frac{K}{W/m^2}$	
	E10.4	HPAR	heat transfer coeff. for parasitic heat loss or gain		

(Repeat No. 4 to 6 cards for additional cases)

Table 2 Sample Input

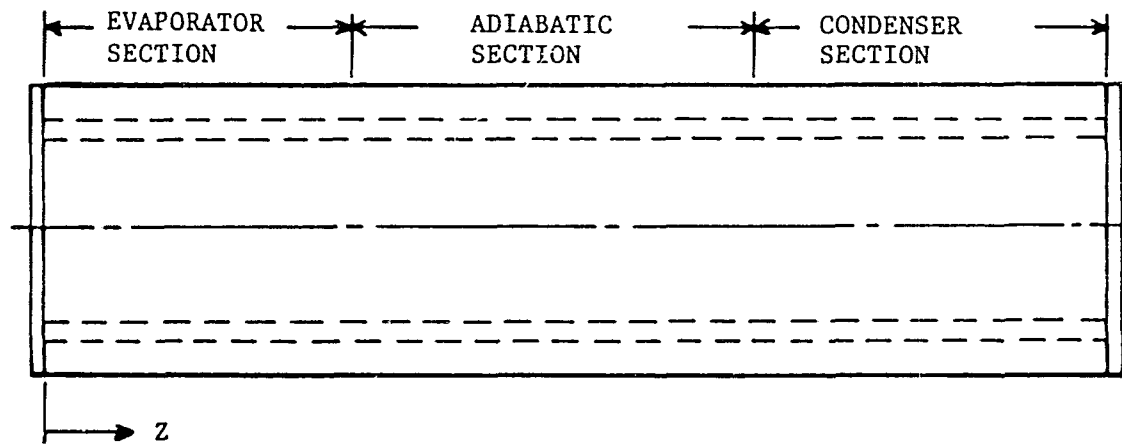
COLUMN NO.

00000000011111111122222222223333333333444444444455555555556666666666
123456789012345678901234567890123456789012345678901234567890123456789

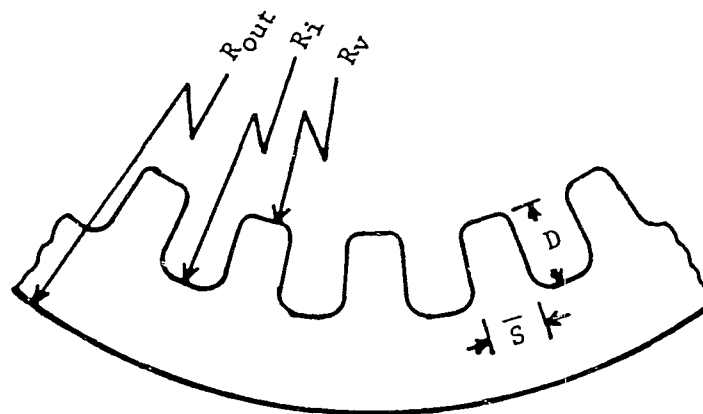
INPUT DATA

	.3048	.4572	.1524		
27	.108E-2	.37E-3	.795E-2	.544E-2	.450E-2
AMMONIA	ALUMINUM				
80.0	250.0	215.0			
	.592E 0	.67E 3	.18E 3		
	1.2E-3\	.6E-2	1.4E-2		
90.0	270.0	500.0	500.0		
0.0	90.0	270.0	360.0		
0.0	.0E 0				

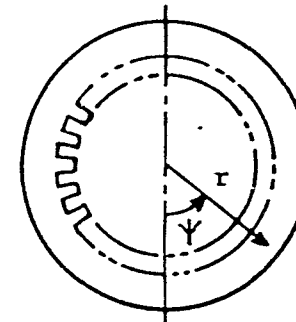
ORIGINAL PAGE IS
OF POOR QUALITY



Heat Pipe Cross-section

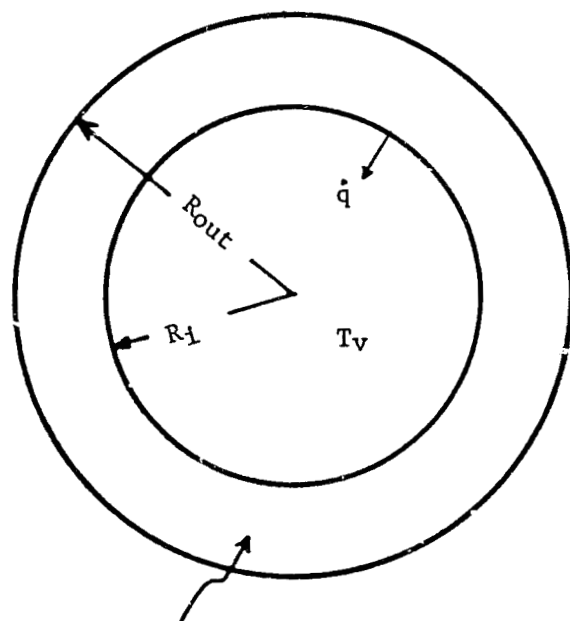


Groove Detail



ORIGINAL PAGE IS
OF POOR QUALITY

Figure 1. Heat Pipe Cross-Section



$$\dot{q} = h_{eq,e} (T_{si}(\gamma, Z) - T_v) \times \text{AREA}$$

OR

$$\dot{q} = h_{eq,c} (T_v - T_{si}(\gamma, Z)) \times \text{AREA}$$

ORIGINAL PAGE IS
OF POOR QUALITY

Figure 2. Hypothetical Inner Wall Surface

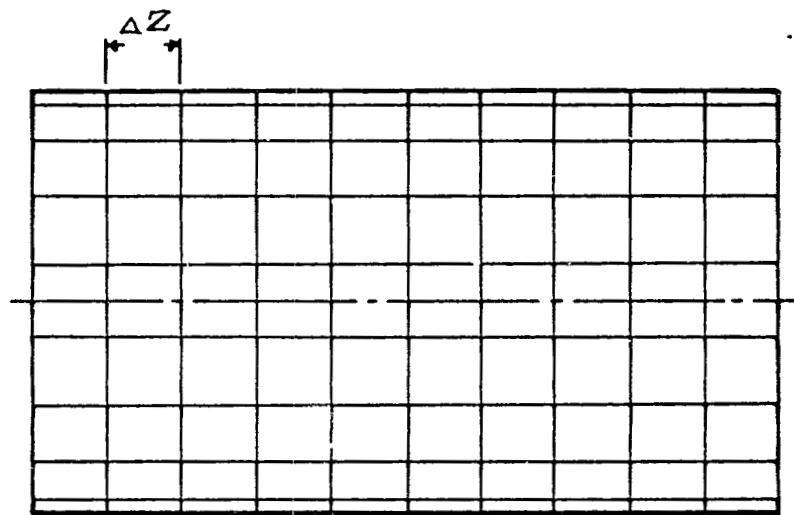
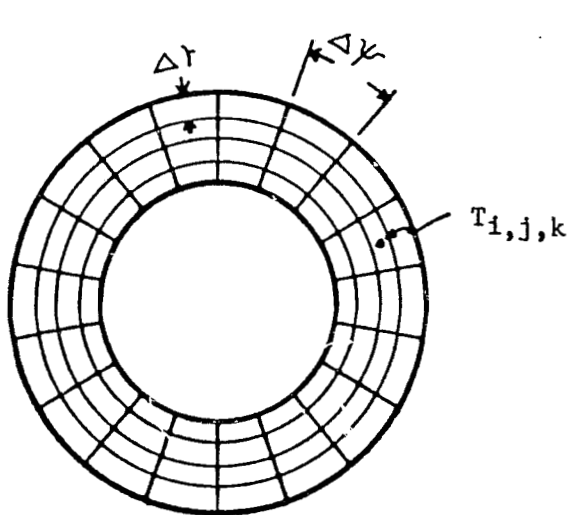
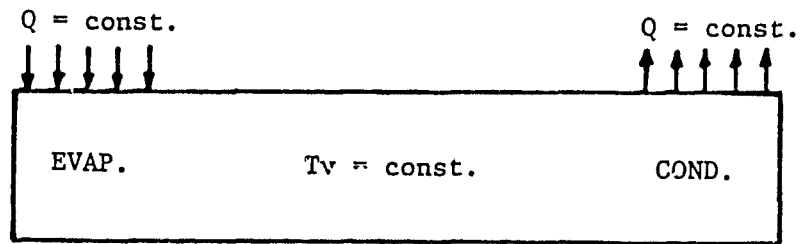


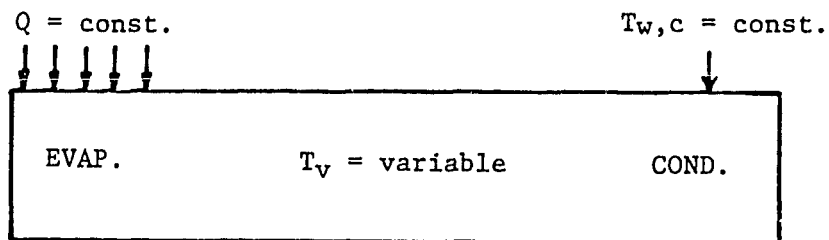
Figure 3. Heat Pipe Model

ORIGINAL PAGE IS
OF POOR QUALITY

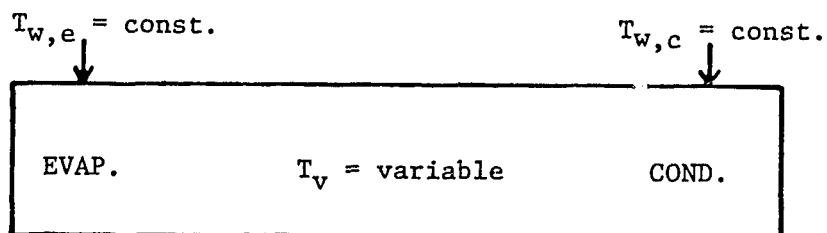
ORIGINAL PAGE IS
OF POOR QUALITY



Type 1



Type 2



Type 3

Figure 4. Exterior Boundary Conditions

ORIGINAL PAGE IS
OF POOR QUALITY

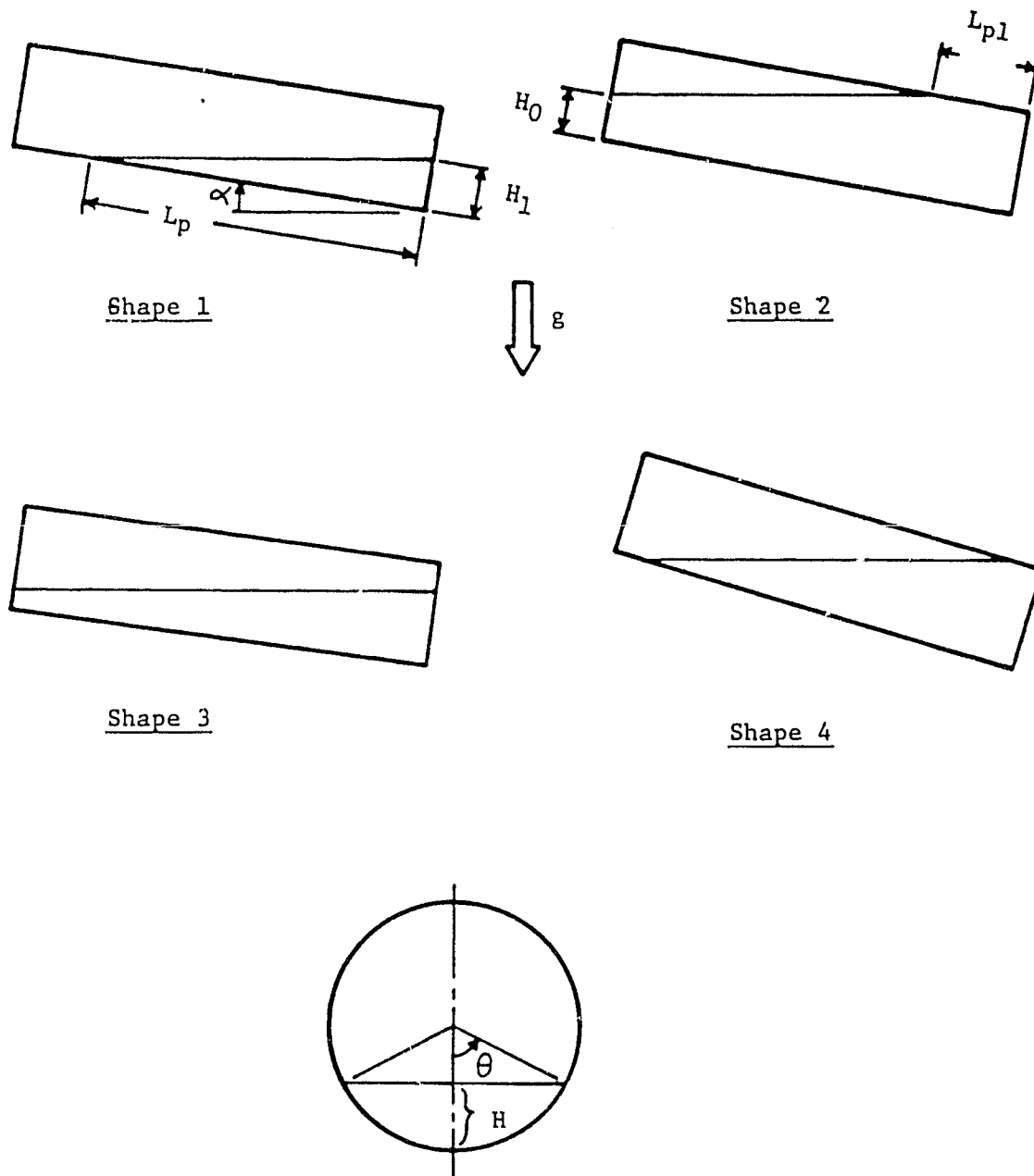
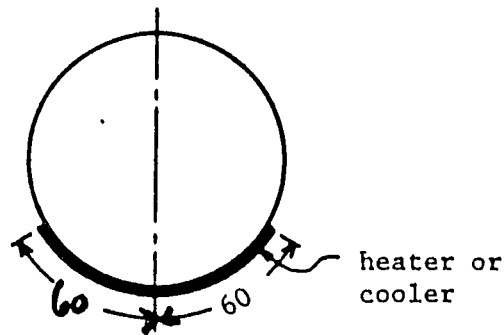


Figure 5. Puddle Shape Classification

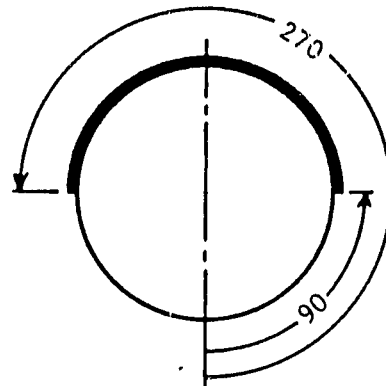
CONCRETE FLOOR IS OF POOR QUALITY

Example 1



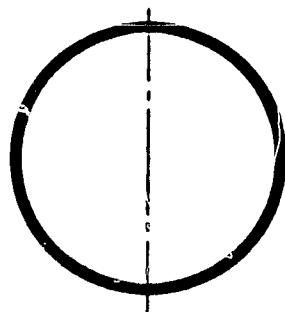
$$\begin{aligned} \gamma_1 &= 0 \text{ (deg.)} , \gamma_2 = 60 \\ \gamma_3 &= 300 \quad \gamma_4 = 360 \end{aligned}$$

Example 2



$$\begin{aligned} \gamma_1 &= 90 , \gamma_2 = 270 \\ \gamma_3 &= 500 , \gamma_4 = 500 \end{aligned}$$

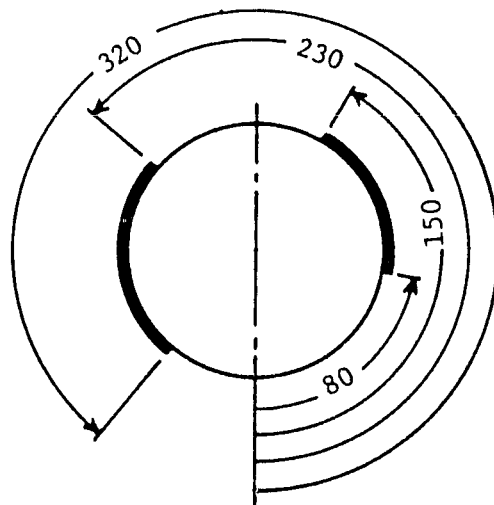
Example 3



(uniform heating or cooling)

$$\begin{aligned} \gamma_1 &= 0 , \gamma_2 = 360 \\ \gamma_3 &= 500 , \gamma_4 = 500 \end{aligned}$$

Example 4



(multiple heating or cooling)

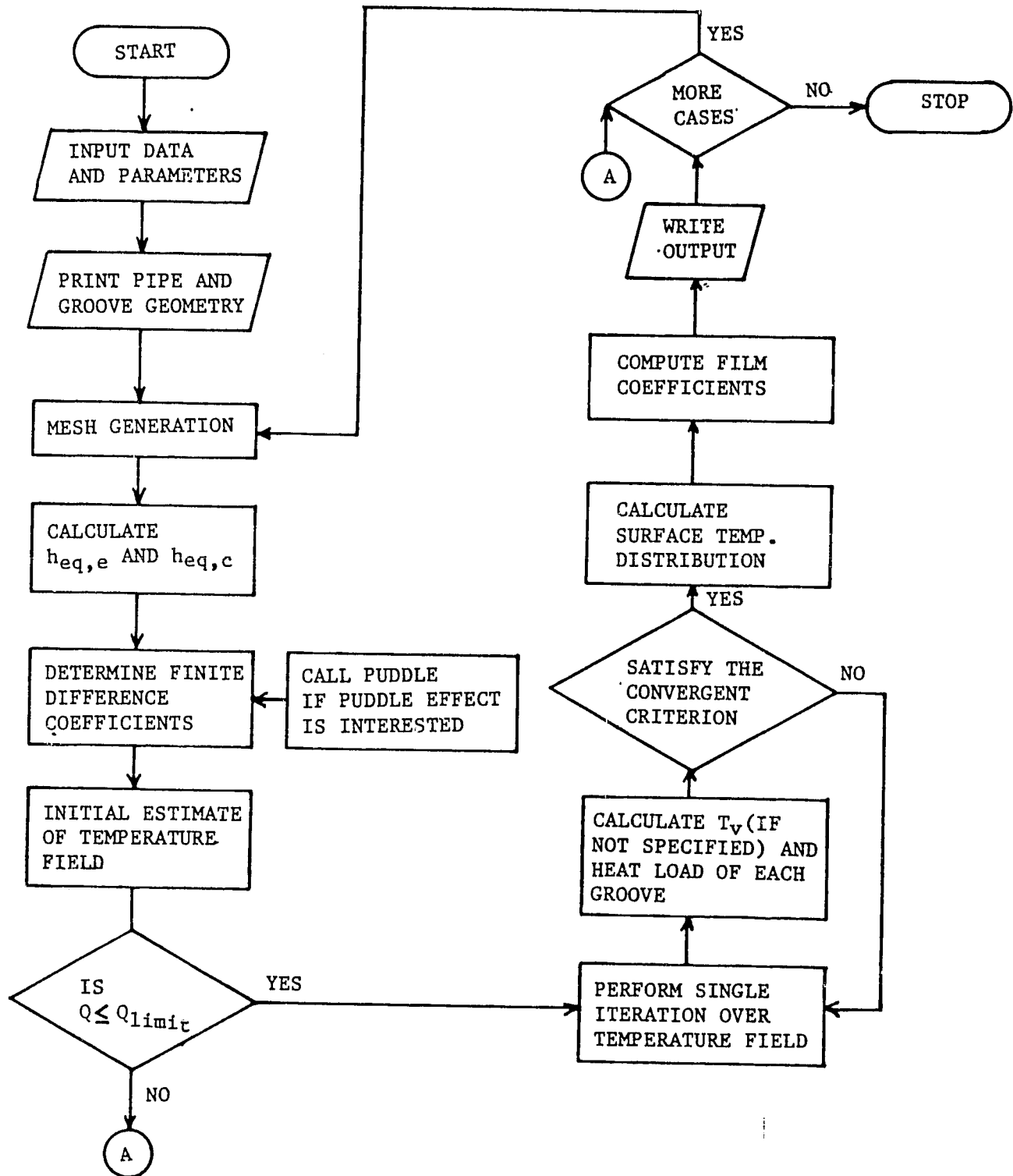
$$\begin{aligned} \gamma_1 &= 80 , \gamma_2 = 150 \\ \gamma_3 &= 230 , \gamma_4 = 320 \end{aligned}$$

Figure 6. Heating and Cooling Zone Specification

APPENDIX A

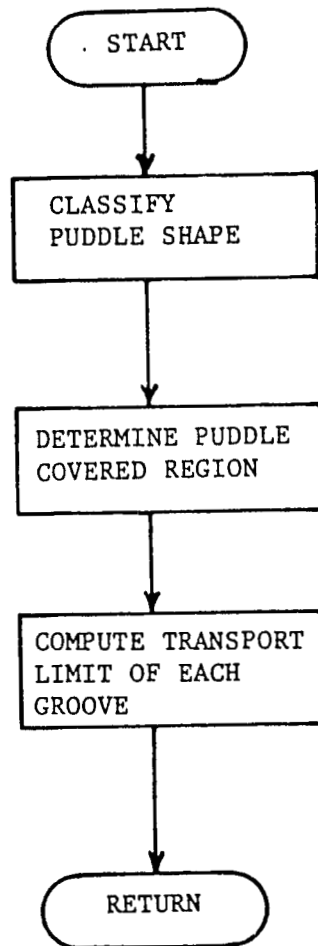
PROGRAM FLOWCHART

MAIN PROGRAM



ORIGINAL PAGE IS
OF POOR QUALITY

SUBROUTINE PUDDLE



APPENDIX B

PROGRAM LISTING

ORIGINAL PAGE 10
OF POOR QUALITY

015/360 FORTRAN H

COMPILER OPTIONS - NAME= MAIN,OPT=02,LINFCN1=82,SIZE=0000K,

SOURCE,FBCDIC,NOLIST,NODECK,LOAD,MAP,NODE11,10,XREF

```

1SN 0002      DIMENSION R(7),PSI(35),DEGPSI(35),Z(32),DR(7),NPST(35),DZ(32)
1SN 0003      DIMENSION I(5,29,27),II(5,29,27),IIN(29,27),TOUIT(29,27)
1SN 0004      DIMENSION PSIF(4),PSIC(4),NGF(4),NGC(4)
1SN 0005      DIMENSION C(4000,R),ES(4000),CIDMA(7),OTDMA(7)
1SN 0006      DIMENSION CONDL(5),CONDW(5),RHO(5),Q(5),TV(5),TCOHD(5),TEVAP(5),
                XSM(5),FL(5),XST(5)
1SN 0007      DIMENSION QMAX(5),QMAXGR(35),QSINGL(35)
1SN 0008      DIMENSION IFLUID(5),JPIPE(10)
1SN 0009      COMMON C,Z,XLF,XLAD,XLC,XL,RV,NGRV,XSTHT,L,M,MM,N,NN,NNN,
                RHOL,XSMAS,FLV,QMXO,QMAXGR

```

C

C

C

NOMENCLATURE

C

C

C(MP,N) = FINITE DIFFERENT COEFFICIENTS (W/K)

C

CONL,CONDL = FLUID THERMAL CONDUCTIVITY (W/(M*K))

C

CONW,CONDW = PIPE WALL THERMAL CONDUCTIVITY (W/(M*K))

C

NPST(J) = INCREMENT IN PSI ABOUT J (RAD.)

C

DR(I) = INCREMENT IN R ABOUT I (M)

C

DZ(K) = INCREMENT IN Z ABOUT K (M)

C

DTSPEC = SPECIFIED ACCEPTABLE CHANGE IN TEMP. BETWEEN SUCCESSIVE
ITERATIONS (K)

C

FL,FLV = EVAPORATOR FND ELEVATION (M)

C

FILMEV = EVAPORATOR FILM COEFFICIENT (W/(M**2*K))

C

FILMCO = CONDENSER FILM COEFFICIENT (W/(M**2*K))

C

FS = HEAT GENERATION TERM (W)

C

GDEPTH = GROOVE DEPTH (M)

C

HCON = EQUIVALENT CONDENSER FILM COEFF. (W/(M**2*K))

C

HEVP = EQUIVALENT EVAPORATOR FILM COEFF. (W/(M**2*K))

C

HPAR = HEAT TRANSFER COEFF. FOR PARASITIC HEAT LOSS OR GAIN
(W/(M**2*K))

C

IFLUID = NAME OF WORKING FLUID

C

IPUDL = CODE FOR PUDDLE EFFECT

→

C

IPUDL = 1, PUDDLE EFFECT IS NOT INCLUDED

C

2, PUDDLE EFFECT IS INCLUDED

C

INIT = NO. OF ITERATIONS PER LOOP OF ITERATION

C

JPIPE = PIPE WALL MATERIAL

→

C

KTYPE = CODE TO SPECIFY BOUNDARY CONDITIONS (SEE THE MANUAL FOR
THIS CODE)

C

MGRAVT = CODE FOR GRAVITY EFFECT

→

C

MGRAVT = 1, ZERO-G CONDITION

C

2, ONE-G CONDITION

C

MP,MPAR = STORAGE PARAMETER

C

NCASE = NO. OF CASES TO BE RUN

C

NGKV = NO. OF GROOVES

C

NDIVR = NO. OF DIVISIONS IN R-DIRECTION

C

NDIVSI = NO. OF DIVISIONS IN PSI-DIRECTION

C

NDIVZ = NO. OF DIVISIONS IN Z-DIRECTION

C

NDIVZF = NO. OF AXIAL DIVISIONS IN EVAPORATOR

C

NDIVZA = NO. OF AXIAL DIVISIONS IN ADIABATIC SECTION

C

NDIVZC = NO. OF AXIAL DIVISIONS IN CONDENSER

C

NGC(1),(2),(3),(4) = PSTC CONVERTED TO GROOVE NUMBERS

C

NGE(1),(2),(3),(4) = PSIE CONVERTED TO GROOVE NUMBERS

ORIGINAL PAGE IS
OF POOR QUALITY

C NITN = TOTAL NUMBER OF ITERATIONS
 C PSI(J) = ANGLE OF MINDS AT J, (RAD.)
 C PSIC(1),(2),(3),(4) = ANGLES TO SPECIFY COOLING ZONE (DEG.)
 C PSIE(1),(2),(3),(4) = ANGLES TO SPECIFY HEATING ZONE (DEG.)
 C Q,TOTL = TOTAL HEAT INPUT (W)
 C QMAX = MAX. HEAT TRANSPORT OF PIPE FOR OPTIMUM CHARGE (W)
 C QMXD = MAX. HEAT TRANSPORT OF SINGLE GROOVE (W)
 C QMAXGR = MAX. HEAT TRANSPORT OF SINGLE GROOVE, ADJUSTED FOR
 C TILT AND PUDDLE EFFECT
 C QMAXHP = MAX. HEAT TRANSPORT OF PIPE, ADJUSTED FOR TILT AND
 C PUDDLE EFFECT
 C QTRNSP = NET HEAT TRANSPORT OF PIPE (W)
 C QSINGL = NET HEAT TRANSPORT OF EACH GROOVE (W)
 C RQUT = PIPE OUTER RADIUS (M)
 C RIN = PIPE INNER RADIUS (GROOVE ROOT RADIUS) (M)
 C RV = VAPOR CORE RADIUS (GROOVE TIP RADIUS) (M)
 C RHOI,RHO = FLUID DENSITY (KG/M**3)
 C RIIJ = RADIUS OF MINDS AT J
 C TEMPS = AMBIENT TEMPERATURE (K)
 C TCOND,IHC = CONDENSER WALL SURFACE TEMP. (K)
 C TEVAP,IWE = EVAPORATOR WALL SURFACE TEMP. (K)
 C TV,TVAP = VAPOR TEMPERATURE (K)

ORIGINAL PAGE IS
OF POOR QUALITY

```

C      TWCAY = AVERAGE CONDENSER WALL SURFACE TEMP. (K)
C      THEAV = AVERAGE EVAPORATOR WALL SURFACE TEMP. (K)
C      TIN = PIPE INNER SURFACE TEMP. (K)
C      TOUT = PIPE OUTER SURFACE TEMP. (K)
C      TEMPE = ESTIMATED EVAPORATOR TEMP. (K)
C      TEMPC = ESTIMATED CONDENSER TEMP. (K)
C      TNGRC = TOTAL NUMBER OF GROOVES IN COOLING ZONE
C      TNGPF = TOTAL NUMBER OF GROOVES IN HEATING ZONE
C      W = RELAXATION PARAMETER
C      WIDTH = AVERAGE GROOVE LAND WIDTH (M)
C      XLF = LENGTH OF EVAPORATION SECTION (M)
C      XLAD = LENGTH OF ADIABATIC SECTION (M)
C      XLC = LENGTH OF CONDENSER SECTION (M)
C      XL = TOTAL PIPE LENGTH (M)
C      XSTHT,XST = STATIC HEIGHT (M)
C      XSMAS,XSM = EXCESS MASS CHARGE (KG)
C      XPDL = PUNDLE LENGTH (M)
C      XTMS = TRANSPORT LENGTH (M)
C      XSVOL = EXCESS VOLUME (M**3)
C      Z(K) = POSITION IN Z-DIRECTION OF NODES AT K (M)
C
C      *****
C
C      FUNCTION DEFINITIONS
C
C      *****
C
ISN 0010      DRP(I) = (DR(I+1)+DR(I))/2.
ISN 0011      DRN(I) = (DR(I)+DR(I-1))/2.
ISN 0012      DZP(K) = (DZ(K+1)+DZ(K))/2.
ISN 0013      DZN(K) = (DZ(K)+DZ(K-1))/2.
ISN 0014      C1(I,J,K) = CONW*(R(I)-DRN(I)/2.)*DPSI(J)*DZ(K)/DRN(I)
ISN 0015      C2(I,J,K) = CONW*(R(I)+DRP(I)/2.)*DPSI(J)*DZ(K)/DRP(I)
ISN 0016      C3(I,J,K) = CONW*DZ(K)*ALOG((R(I)+DRP(I)/2.)/(R(I)-DRN(I)/2.))/
ISN 0017      1DPSI(J)
ISN 0017      C4(I,J,K) = CONW*DZ(K)*ALOG((R(I)+DRP(I)/2.)/(R(I)-DRN(I)/2.))/
ISN 0017      1DPSI(J)
ISN 0018      C5(I,J,K) = CONW*DPSI(J)*((R(I)+DRP(I)/2.)**2-(R(I)-DRN(I)/2.)
ISN 0018      1**2)/2.)/DZN(K)
ISN 0019      C6(I,J,K) = CONW*DPSI(J)*((R(I)+DRP(I)/2.)**2-(R(I)-DRN(I)/2.)
ISN 0019      1**2)/2.)/DZP(K)
ISN 0020      MPAR(I,J,K) = (K-1)*L*M + (I-1)*M + J
C
C      *****
C
C      INPUT SECTION
C
C      *****
C
C      INPUT OPERATING PARAMETERS
C
ISN 0021      IPUNDL = 2
ISN 0022      KTYPE = 1
ISN 0023      MGKAVI = 2
C
C      INPUT PIPE GEOMETRY
C
ISN 0024      READ(5,10) XLF,XLAD,XLC

```

ORIGINAL PAGE 17
OF POOR QUALITY

ISN 0025 XL = XLF + XLAD + XLC

C
C INPUT GROOVE GEOMETRY

ISN 0026 READ(5,11) NGRV,DEPTH,WIDTH,ROUT,RIN,RV

C
C INPUT FLUID AND PIPE MATERIAL NAMES

ISN 0027 READ(5,12) (IFLUID(I),I=1,5),(JPIPE(J),J=1,10)

C
C INPUT OPERATING CONDITIONS AND FLUID AND PIPE MATERIAL PROPERTIES
C FOR EACH RUN

ISN 0028 NCASE = 1

ISN 0029 DO 20 IRIIN=1,NCASE

ISN 0030 GO TO (1,2,3),KTYPE

ISN 0031 1 READ(5,13) O(IRIIN),TV(IRIIN),OMAX(IRIIN)

ISN 0032 GO TO 4

ISN 0033 2 READ(5,13) O(IRIIN),TCOND(IRIIN),OMAX(IRIIN)

ISN 0034 GO TO 4

ISN 0035 3 READ(5,13) TEVAP(IRIIN),TCOND(IRIIN),OMAX(IRIIN)

ISN 0036 4 CONTINUE

ORIGINAL PAGE IS
OF POOR QUALITY

```
-----
ISN 0037      READ(5,16) CONDL(IRUN),KHO(IRUN),CONDW(IRUN)
C             IN ZERO-G CONDITION SKIP THE NEXT CARD
ISN 0038      IF(MGRAV1.EQ. 1) GO TO 20
ISN 0040      READ(5,17) XSM(IRUN),EL(IRUN),XST(IRUN)
ISN 0041      20 CONTINUE
C
ISN 0042      READ(5,14) (PSIF(I),I=1,4)
ISN 0043      READ(5,14) (PSIC(J),J=1,4)
ISN 0044      READ(5,15) 1FMPS,HPAR
C
ISN 0045      DO 199 IJ=1,4
ISN 0046      NGC(IJ) = PSIF(IJ)*N/4V/360.
ISN 0047      NGC(IJ) = PSIC(IJ)*NGRV/360.
ISN 0048      199 CONTINUE
C
ISN 0049      10 FORMAT(3F10.4)
ISN 0050      11 FORMAT(15,5F10.4)
ISN 0051      12 FORMAT(5A2,10A2)
ISN 0052      13 FORMAT(3F10.5)
ISN 0053      16 FORMAT(3F15.4)
ISN 0054      17 FORMAT(3F15.4)
ISN 0055      14 FORMAT(4F10.3)
ISN 0056      15 FORMAT(F10.3,F10.4)
C
C INPUT PARAMETERS
C
ISN 0057      NDIVR = 3
ISN 0058      NDIVSI = NGRV
ISN 0059      NDIVZE = 10
ISN 0060      NDIVZA = 5
ISN 0061      NDIVZC = 10
ISN 0062      NDIVZ = NDIVZE + NDIVZA + NDIVZC
ISN 0063      L = NDIVR
ISN 0064      LL = L+1
ISN 0065      LLL = L+2
ISN 0066      M = NDIVSI
ISN 0067      MM = M+1
ISN 0068      MMM = M+2
ISN 0069      N = NDIVZ
ISN 0070      NN = N+1
ISN 0071      NNN = N+2
ISN 0072      INIT = 5
ISN 0073      W = 1.0
ISN 0074      OTSPEC = .01
ISN 0075      PAI = 3.14159
C
C *****
C
C OUTPUT PIPE AND GROOVE DIMENSIONS
C
C *****
C
ISN 0076      WRITE(6,921)
ISN 0077      921 FORMAT('1',2HX,'*****')
ISN 0078      WRITE(6,901)
ISN 0079      901 FORMAT(20X,'THERMAL ANALYSIS OF AXIALLY GROOVED HEAT PIPE')
ISN 0080      WRITE(6,922)
ISN 0081      922 FORMAT(29X,'*****')
```

OF POOR QUALITY

```

1SN 0082      WRITE(6,960) (IFLUID(I),I=1,5),(JPIPE(J),J=1,10)
1SN 0083      960 FORMAT(///,15X,'NAMES OF WORKING FLUID AND PIPE MATERIAL',//,
1              20X,'WORKING FLUID',T74,5A2/
1              20X,'PIPE MATERIAL',T74,10A2)
1SN 0084      * RHOIT = RHOIT*2.
1SN 0085      * DIN = DIN*2.
1SN 0086      WRITE(6,902) XLF,XLAD,XLC,XL,RHOIT,DIN,RV
1SN 0087      902 FORMAT(///,15X,'HEAT PIPE DIMENSIONS',//,
1              20X,'EVAPORATOR LENGTH(M)',T70,F15.5/
1              20X,'ADIABATIC LENGTH(M)',T70,F15.5/
1              20X,'CONDENSER LENGTH(M)',T70,F15.5/
1              20X,'TOTAL PIPE LENGTH(M)',T70,F15.5/
1              20X,'PIPE OUTER DIAMETER(M)',T70,F15.5/
1              20X,'PIPE INNER DIAMETER(M)',T70,F15.5/
1              20X,'VAPOR CORE RADIUS(M)',T70,F15.5)
1SN 0088      WRITE(6,903) NGRV,GDEPTH,WIDTH
1SN 0089      903 FORMAT(///,15X,'GROOVE DIMENSIONS',//,
1              20X,'NUMBER OF GROOVES',T75,I5/
1              20X,'GROOVE DEPTH(M)',T70,F15.5/
1              20X,'AVERAGE LAND WIDTH(M)',T70,F15.5)
C
C      OUTPUT HEATING AND COOLING MODES

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

C
ISN 0090      WRITE(6,976)
ISN 0091      976 FORMAT(//,15X,'HEATING AND COOLING MODES')
ISN 0092      IF(NGF(1) .EQ. 0 .AND. NGF(2) .EQ. M) GO TO 977
ISN 0094      WRITE(6,979) PSIF(1),PSIF(2)
ISN 0095      979 FORMAT(//,20X,'EVAPORATOR REGION',150,'NON-UNIFORM HEATING',/,
1              150,'HEATING REGION COVERS FROM PSI=',F5.1,' DEG TO PSI=
1              ,F5.1,' DEG')
ISN 0096      IF(NGF(3) .LT. M) WRITE(6,980) PSIF(3),PSIF(4)
ISN 0098      980 FORMAT(67X,'AND FROM PSI=',F5.1,' DEG TO PSI=',F5.1,' DEG')
ISN 0099      GO TO 981
ISN 0100      977 WRITE(6,978)
ISN 0101      978 FORMAT(//,20X,'EVAPORATOR REGION', 70,'UNIFORM HEATING')
ISN 0102      981 CONTINUE
ISN 0103      IF(NGC(1) .EQ. 0 .AND. NGC(2) .EQ. M) GO TO 982
ISN 0105      WRITE(6,984) PSIC(1),PSIC(2)
ISN 0106      984 FORMAT(//,20X,'CONDENSER REGION',150,'NON-UNIFORM COOLING',/,
1              150,'COOLING REGION COVERS FROM PSI=',F5.1,' DEG TO PSI=
1              ,F5.1,' DEG')
ISN 0107      IF(NGC(3) .LT. M) WRITE(6,985) PSIC(3),PSIC(4)
ISN 0109      985 FORMAT(67X,'AND FROM PSI=',F5.1,' DEG TO PSI=',F5.1,' DEG')
ISN 0110      GO TO 986
ISN 0111      982 WRITE(6,983)
ISN 0112      983 FORMAT(//,20X,'CONDENSER REGION',170,'UNIFORM COOLING')
ISN 0113      986 CONTINUE
C
C *****
C
C MESH GENERATION
C
C *****
C
ISN 0114      DO 101 I=2,LL
ISN 0115      DR(I) = (ROUT - RIN)/L
ISN 0116      R(I) = RIN + (I-1.5)*DR(I)
ISN 0117      101 CONTINUE
ISN 0118      DR(1) = 0.0
ISN 0119      R(1) = RIN
ISN 0120      DR(LLL) = 0.0
ISN 0121      R(LLL) = ROUT
C
ISN 0122      DO 102 J=1,MMM
ISN 0123      DPST(J) = 2.0*PAI/M
ISN 0124      PSI(J) = (J-1.5)*DPST(J)
ISN 0125      102 CONTINUE
ISN 0126      PSI(1) = 0.0
ISN 0127      PSI(MMM) = 2.0*PAI
C
ISN 0128      NZ(1) = 0.0
ISN 0129      Z(1) = 0.0
ISN 0130      NDVFI = NDIVZF + 1
ISN 0131      DO 103 K=2,NDVFI
ISN 0132      NZ(K) = XLF/NDIVZF
ISN 0133      Z(K) = (K-1.5)*NZ(K)
ISN 0134      103 CONTINUE
ISN 0135      NDVFI = NDIVZF + 2
ISN 0136      NDVFA1 = NDIVZF + NDIVFA + 1
ISN 0137      DO 104 K=NDVFI,NDVFA1

```

POOR QUALITY

```
ISN 0138      DZ(K) = XLAD/NDIV7A
ISN 0139      Z(K) = XLE + (K - NDIV7E - 1.5)*DZ(K)
ISN 0140      104 CONTINUE
ISN 0141      NDVFA2 = NDIV7E + NDIV7A + 2
ISN 0142      DO 105 K=NDVFA2,NN
ISN 0143      DZ(K) = XLC/NDIV7C
ISN 0144      Z(K) = XLE + XLAD + (K - NDIV7E - NDIV7A - 1.5)*DZ(K)
ISN 0145      105 CONTINUE
ISN 0146      DZ(NNN) = 0.0
ISN 0147      Z(NNN) = XI
C
C *****
C
C      RUIN THE PROGRAM FOR THE NUMBER OF CASES SPECIFIED
C
C *****
C
ISN 0148      DO 50 IRUN=1,NCASE
C
ISN 0149      CONI = CONDI(IRUN)
ISN 0150      RHOL = RHO(IRUN)
ISN 0151      CONW = CONDW(IRUN)
```


ORIGINAL PAGE IS
OF POOR QUALITY

```

C
C COMPUTE SINGLE GROOVE TRANSPORT LIMIT
ISN 0152 IF(MGRAVT.EQ.1) GO TO 120
C
C FOR ONE-G CONDITION (POONLE EFFECT IS CONSIDERED LATER)
ISN 0154 FLV = FL(IRUN)
ISN 0155 XSTHT = XST(IRUN)
ISN 0156 XSMAS = XSM(IRUN)
ISN 0157 OMAXO = OMAX(IRUN)/NGRV
ISN 0158 DO 121 J=2,MM
ISN 0159 OMAXGR(J) = OMAXO*(1. - FLV/XSTHT)
ISN 0160 IF(OMAXGR(J).LE.0.0) OMAXGR(J)=0.0
ISN 0162 121 CONTINUE
ISN 0163 GO TO 122
C
ISN 0164 120 CONTINUE
C
C FOR ZERO-G CONDITION
ISN 0165 OMAXO = OMAX(IRUN)/NGRV
ISN 0166 DO 123 J=2,MM
ISN 0167 OMAXGR(J) = OMAXO
ISN 0168 123 CONTINUE
C
ISN 0169 122 CONTINUE
C
C *****
C
C CALCULATIONS OF EVAPORATOR AND CONDENSER EQUIVALENT HEAT
C TRANSFER COEFFICIENTS
C
C *****
ISN 0170 HEVP = (NGRV*CONL/(2.*PAI*RIIN))/(.0701+(CONL/CONW)*(GDEPTH/WIDTH))
ISN 0171 HCON = (NGRV*CONL/(2.*PAI*RIIN))/(.0701+(CONL/CONW)*(GDEPTH/WIDTH))
C
C *****
C
C STORAGE OF COEFFICIENTS
C
C *****
C
ISN 0172 DO 200 K=2,NN
ISN 0173 DO 200 J=2,MM
ISN 0174 DO 200 I=2,LL
ISN 0175 MP = MPAR(I,J,K)
C
ISN 0176 C(MP,1) = C1(I,J,K)
ISN 0177 C(MP,2) = C2(I,J,K)
ISN 0178 C(MP,3) = C3(I,J,K)
ISN 0179 C(MP,4) = C4(I,J,K)
ISN 0180 C(MP,5) = C5(I,J,K)
ISN 0181 C(MP,6) = C6(I,J,K)
ISN 0182 C(MP,8) = 0.0
ISN 0183 ES(MP) = 0.0
ISN 0184 THUT(J,K) = 0.0
C
C SPECIFY BOUNDARY CONDITIONS
C

```

CONTINUED FROM PAGE 1 OF POOR QUALITY

ISN 0185 *NODES CONTACTING Z=0
IF(K .EQ. 2) C(MP,5)=0.0

ISN 0187 *NODES CONTACTING Z=XL
IF(K .EQ. NN) C(MP,6)=0.0

ISN 0189 *NODES CONTACTING R=ROOT
IF(I .NE. LL) GO TO 200

ISN 0191 PARASITIC HEAT LOSS OR GAIN
$$C(MP,2) = C2(I,J,K)*(HPAR*DR(LL)/CONW1)/(2.0 + HPAR*DR(LL)/CONW1)$$

ISN 0192 CLASSIFY BOUNDARY CONDITIONS INTO THREE TYPES
GO TO (201,202,203), KTYPE

ISN 0193 201 CONTINUE
TYPE 1 BOUNDARY CONDITION

ORIGINAL PAGE IS
OF POOR QUALITY

```

ISN 0194      OTOTL = O(IRIN)
ISN 0195      TVAP = TV(IRIN)
C
C      EVAPORATOR (TOTAL HEAT INPUT SPECIFIED)
C
ISN 0196      IF (NGF(3) .GT. M) GO TO 204
ISN 0198      TNGRF = (NGF(2) - NGF(1)) + (NGF(4) - NGF(3))
ISN 0199      GO TO 205
ISN 0200      204 TNGRF = NGF(2) - NGF(1)
ISN 0201      205 CONTINUE
ISN 0202      IF (J .LT. (NGF(1)+2)) GO TO 210
ISN 0204      IF (J .GE. (NGF(2)+2) .AND. J .LT. (NGF(3)+2)) GO TO 210
ISN 0206      IF (J .GE. (NGF(4)+2)) GO TO 210
ISN 0208      IF (I(K) .GT. XL F) GO TO 210
ISN 0210      FS(MP) = DZ(K)*OTOTL/(TNGRF*XL F)
ISN 0211      210 CONTINUE
C
C      CONDENSER (TOTAL HEAT OUTPUT SPECIFIED)
C
ISN 0212      IF (NGC(3) .GT. M) GO TO 211
ISN 0214      TNGRC = (NGC(2) - NGC(1)) + (NGC(4) - NGC(3))
ISN 0215      GO TO 212
ISN 0216      211 TNGRC = NGC(2) - NGC(1)
ISN 0217      212 CONTINUE
ISN 0218      IF (J .LT. (NGC(1)+2)) GO TO 220
ISN 0220      IF (J .GE. (NGC(2)+2) .AND. J .LT. (NGC(3)+2)) GO TO 220
ISN 0222      IF (J .GE. (NGC(4)+2)) GO TO 220
ISN 0224      IF (I(K) .LT. (XL F+XL AN)) GO TO 220
ISN 0226      FS(MP) = -DZ(K)*OTOTL/(TNGRC*XL C)
ISN 0227      220 CONTINUE
ISN 0228      GO TO 200
C
ISN 0229      202 CONTINUE
C
C      TYPE 2 BOUNDARY CONDITION
C
ISN 0230      OTOTL = O(IRIN)
ISN 0231      TWC = TCOND(IRIN)
C
C      EVAPORATOR (TOTAL HEAT INPUT SPECIFIED)
C
ISN 0232      IF (NGF(3) .GT. M) GO TO 221
ISN 0234      TNGRF = (NGF(2) - NGF(1)) + (NGF(4) - NGF(3))
ISN 0236      GO TO 222
ISN 0237      221 TNGRF = NGF(2) - NGF(1)
ISN 0238      222 CONTINUE
ISN 0239      IF (J .LT. (NGF(1)+2)) GO TO 223
ISN 0240      IF (J .GE. (NGF(2)+2) .AND. J .LT. (NGF(3)+2)) GO TO 223
ISN 0242      IF (J .GE. (NGF(4)+2)) GO TO 223
ISN 0244      IF (I(K) .GT. XL F) GO TO 223
ISN 0246      FS(MP) = DZ(K)*OTOTL/(TNGRF*XL F)
ISN 0247      223 CONTINUE
C
C      CONDENSER (OUTER SURFACE TEMPERATURE SPECIFIED)
C
ISN 0248      IF (J .LT. (NGC(1)+2)) GO TO 224
ISN 0250      IF (J .GE. (NGC(2)+2) .AND. J .LT. (NGC(3)+2)) GO TO 224
ISN 0252      IF (J .GE. (NGC(4)+2)) GO TO 224

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

-----
ISN 0254      IF (7(K) .LT. (XLF+XLAD)) GO TO 224
ISN 0256      TOUT(J,K) = TWC
ISN 0257      C(MP,B) = C2(I,J,K)
ISN 0258      224 CONTINUE
ISN 0259      GO TO 200

      C
ISN 0260      203 CONTINUE
      C
      C TYPE 3 BOUNDARY CONDITION
      C
ISN 0261      TWC = TEVAP(IRUN)
ISN 0262      TWC = TCOND(IRUN)
      C
      C EVAPORATOR (OUTER SURFACE TEMPERATURE SPECIFIED)
      C
ISN 0263      IF (J .LT. (NGF(1)+2)) GO TO 225
ISN 0265      IF (J .GE. (NGF(2)+2) .AND. J .LT. (NGF(3)+2)) GO TO 225
ISN 0267      IF (J .GE. (NGF(4)+2)) GO TO 225
ISN 0269      IF (7(K) .GT. XLF) GO TO 225
ISN 0271      TOUT(J,K) = TWC
ISN 0272      C(MP,B) = C2(I,J,K)
ISN 0273      225 CONTINUE

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

C
C . CONDENSER (OUTER SURFACE TEMPERATURE SPECIFIED)
C
ISN 0274      IF (J .LT. (NGC(1)+2)) GO TO 226
ISN 0276      IF (J .GE. (NGC(2)+2) .AND. J .LT. (NGC(3)+2)) GO TO 226
ISN 0278      IF (J .GE. (NGC(4)+2)) GO TO 226
ISN 0280      IF (Z(K) .LT. (XLF+XLAD)) GO TO 226
ISN 0282      TOUT(J,K) = TW
ISN 0283      C(MP,R) = C2(I,J,K)
ISN 0284      226 CONTINUE
C
ISN 0285      200 CONTINUE
C
C *NODES CONTACTING R=RJA
C THIS PART SPECIFIES ONLY PUDDLE EFFECT
C HEAT TRANSFER CONDITION IS SPECIFIED IN THE ITERATION SECTION
C
ISN 0286      IF (MGRVT .EQ. 1) GO TO 270
ISN 0288      IF (IPUDL .EQ. 1) GO TO 270
ISN 0290      IF (XSMAS .LE. 0.0) GO TO 270
ISN 0292      IF (FLV .LE. 0.0) GO TO 270
C (PUDDLE EFFECT FOR ZERO-ELEVATION IS NOT TREATED IN THIS PROGRAM)
ISN 0294      CALL PUDDLE
ISN 0295      270 CONTINUE
C
C *****
C
C INITIAL ESTIMATE OF TEMPERATURE FIELD
C
C *****
C
ISN 0296      GO TO (250,251,252), KTYPE
C
ISN 0297      250 CONTINUE
C
C FOR TYPE 1 BOUNDARY CONDITION
C
ISN 0298      I = 1
ISN 0299      DO 253 J=1,MMM
ISN 0300      DO 253 K=1,NNN
ISN 0301      T(I,J,K) = TVAP
ISN 0302      253 CONTINUE
ISN 0303      TEMPF = TVAP + OTOTL/(2.*PAI*RIH*HFVP*XLF)
ISN 0304      TEMPC = TVAP - OTOTL/(2.*PAI*RIH*HCON*XLC)
ISN 0305      DO 254 I=2,LL
ISN 0306      DO 254 J=1,MMM
ISN 0307      DO 254 K=1,NNN
ISN 0308      T(I,J,K) = TVAP
ISN 0309      IF (Z(K) .LE. XLF) T(I,J,K)=TEMPF
ISN 0311      IF (Z(K) .GT. (XLF+XLAD)) T(I,J,K)=TEMPC
ISN 0313      254 CONTINUE
ISN 0314      GO TO 260
C
ISN 0315      251 CONTINUE
C
C FOR TYPE 2 BOUNDARY CONDITION
C
ISN 0316      I = 1

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

ISN 0317      TVAP = TWC + 0.071L/(2.*PA1*W1N*HCON*XL C)
ISN 0318      DO 255 J=1,MMM
ISN 0319      DO 255 K=1,NNN
ISN 0320      T(I,J,K) = TVAP
ISN 0321      255 CONTINUE
ISN 0322      TEMPE = TWC + (1.0/(HEVP*XL F) + 1.0/(HCON*XL C))*0.071L/(2.0*PA1 ...
                1 *KIN1)
ISN 0323      DO 256 J=2,LL
ISN 0324      DO 256 J=1,MMM
ISN 0325      DO 256 K=1,NNN
ISN 0326      T(I,J,K) = TVAP
ISN 0327      IF(Z(K) .LE. XL F) T(I,J,K)=TEMPE
ISN 0329      IF(Z(K) .GT. (XL F+XLAD)) T(I,J,K)=TWC
ISN 0331      256 CONTINUE
ISN 0332      GO TO 260
                C
ISN 0333      252 CONTINUE
                C
                C FOR TYPE 3 BOUNDARY CONDITION
                C
ISN 0334      I = 1
ISN 0335      TVAP = (TWF + TWC*(HCON*XL C)/(HEVP*XL F))/(1.0 + (HCON*XL C)/

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

1 (HFVP*XLFI)
ISN 0336 DTOTL = 2.*PAI*RV*(TWF - TWC)/(1.0/(XLFI*HFVP) + 1.0/(XLC*HCIN))
ISN 0337 DO 257 J=1,MMM
ISN 0338 DO 257 K=1,NNN
ISN 0339 T(I,J,K) = TVAP
ISN 0340 257 CONTINUE
ISN 0341 DO 258 I=2,LL
ISN 0342 DO 258 J=1,MMM
ISN 0343 DO 258 K=1,NNN
ISN 0344 T(I,J,K) = TVAP
ISN 0345 IF(I(K).LE.XLFI) T(I,J,K)=TWF
ISN 0347 IF(I(K).GT.(XLFI+XLAD)) T(I,J,K)=TWC
ISN 0349 258 CONTINUE
C
ISN 0350 260 CONTINUE
C
ISN 0351 I = LLL
ISN 0352 DO 261 J=1,MMM
ISN 0353 DO 261 K=1,NNN
ISN 0354 T(I,J,K) = TEMPS
ISN 0355 261 CONTINUE
C
C *****
C
C CHECK FOR TRANSPORT LIMIT
C
C *****
C
C CALCULATE HEAT TRANSPORT LIMIT OF HEAT PIPE
ISN 0356 OMAXHP = 0.0
ISN 0357 DO 262 J=2,MM
ISN 0358 262 OMAXHP = OMAXHP + OMAXGR(J)
C IF TOTAL HEAT INPUT IS LARGER THAN HEAT PIPE TRANSPORT LIMIT,
C TERMINATE COMPUTATION.
ISN 0359 IF(DTOTL.GT.OMAXHP) GO TO 973
C
C *****
C
C ITERATION
C
C *****
C
ISN 0361 IIN = 1
ISN 0362 300 CONTINUE
ISN 0363 DO 350 I=1,INIT
ISN 0364 DO 310 KK=1,N
ISN 0365 K = NNN - KK
ISN 0366 DO 310 J=2,MM
ISN 0367 I = 2
ISN 0368 MP = MPAR(I,J,K)
ISN 0369 TT(I,J,K) = T(I,J,K)
ISN 0370 IF(C(MP,1).LE.(IF-5)) GO TO 302
ISN 0372 IF(T(I,J,K).GT.TVAP) GO TO 301
ISN 0374 C(MP,1) = C1(I,J,K)*(HCIN*DR(2)/CONW)/(2. + HCIN*DR(2)/CONW)
ISN 0375 GO TO 302
ISN 0376 301 C(MP,1) = C1(I,J,K)*(HFVP*DR(2)/CONW)/(2. + HFVP*DR(2)/CONW)
ISN 0377 302 CONTINUE

```

ORIGINAL PAGE IS
OF POOR QUALITY

ISN 0378		$C(MP,7) = C(MP,1) + C(MP,2) + C(MP,3) + C(MP,4) + C(MP,5) +$
		$1 \ C(MP,6)$
ISN 0379		$D = C(MP,1)*T(I-1,J,K) + C(MP,2)*T(I,J-1,K) + C(MP,4)*T(I,J+1,K)$
		$1 + C(MP,5)*T(I,J,K-1) + C(MP,6)*T(I,J,K+1)$
ISN 0380		$CTDMA(I) = -C(MP,2)/C(MP,7)$
ISN 0381		$DTDMA(I) = D/C(MP,7)$
	C	
ISN 0382		$DO 303 I=3,1$
ISN 0383		$MP = MPAR(I,J,K)$
ISN 0384		$TI(I,J,K) = T(I,J,K)$
ISN 0385		$D = C(MP,3)*T(I,J-1,K) + C(MP,4)*T(I,J+1,K) + C(MP,5)*T(I,J,K-1)$
		$1 + C(MP,6)*T(I,J,K+1)$
ISN 0386		$C(MP,7) = C(MP,1) + C(MP,2) + C(MP,3) + C(MP,4) + C(MP,5) +$
		$1 \ C(MP,6)$
ISN 0387		$DFN = C(MP,7) + C(MP,1)*CTDMA(I-1)$
ISN 0388		$CTDMA(I) = -C(MP,2)/DFN$
ISN 0389		$DTDMA(I) = (D + C(MP,1)*DTDMA(I-1))/DFN$
ISN 0390	303	CONTINUE
	C	
ISN 0391		$I = LL$
ISN 0392		$MP = MPAR(I,J,K)$
ISN 0393		$TI(I,J,K) = T(I,J,K)$

ORIGINAL PAGE IS
OF POOR QUALITY

```

-----
ISN 0394      D = C(MP,2)*T(I+1,J,K) + C(MP,3)*T(I,J-1,K) + C(MP,4)*T(I,J+1,K) +
              1 C(MP,5)*T(I,J,K-1) + C(MP,6)*T(I,J,K+1) + FS(MP) + C(MP,8)*
              1 TOUT(J,K)
ISN 0395      C(MP,7) = C(MP,1) + C(MP,2) + C(MP,3) + C(MP,4) + C(MP,5) +
              1 C(MP,6) + C(MP,8)
ISN 0396      DEN = C(MP,7) + C(MP,1)*OTDMA(I-1)
ISN 0397      OTDMA(I) = (D + C(MP,1)*OTDMA(I-1))/DEN
              C
              C TEMPERATURE CALCULATIONS
              C
ISN 0398      I = LL
ISN 0399      T(I,J,K) = OTDMA(I)
ISN 0400      DO 304 I=2,L
ISN 0401      I = ILL - J
ISN 0402      T(I,J,K) = OTDMA(I) - CTDMA(I)*T(I+1,J,K)
ISN 0403      304 CONTINUE
              C
              C RELAXATION
              C
ISN 0404      DO 305 I=2,LL
ISN 0405      T(I,J,K) = (1.0 - W)*T(I,J,K) + W*T(I,J,K)
ISN 0406      305 CONTINUE
ISN 0407      DO 306 I=2,LL
ISN 0408      IF(J.FO. 2) T(I,MM,K)=T(I,J,K)
ISN 0410      IF(J.FO. MM) T(I,I,K)=T(I,J,K)
ISN 0412      306 CONTINUE
              C
ISN 0413      310 CONTINUE
              C
              C VAPOR TEMPERATURE AND TOTAL HEAT TRANSPORT CALCULATIONS
              C
ISN 0414      TIVAP = TVAP
ISN 0415      I = 2
ISN 0416      DO 315 K=2,NN
ISN 0417      DO 315 J=2,MM
ISN 0418      MP = MPAR(I,J,K)
ISN 0419      IF(C(MP,1).LE. .1F-5) GO TO 317
ISN 0421      IF(T(I,J,K).GT. TVAP) GO TO 316
ISN 0423      C(MP,1) = C1(I,J,K)*(HCON*DR(2)/CONW)/(2. + HCON*DR(2)/CONW)
ISN 0424      GO TO 317
ISN 0425      316 C(MP,1) = C1(I,J,K)*(HFVP*DR(2)/CONW)/(2. + HFVP*DR(2)/CONW)
ISN 0426      317 CONTINUE
ISN 0427      C(MP,7) = C(MP,1) + C(MP,2) + C(MP,3) + C(MP,4) + C(MP,5) +
              1 C(MP,6)
ISN 0428      CPRIME = C(MP,7) - C(MP,1) + C1(I,J,K)
ISN 0429      TIN(J,K) = (1.0/C1(I,J,K))*(CPRIME*T(I,J,K) - C(MP,2)*T(I+1,J,K)
              1 - C(MP,3)*T(I,J-1,K) - C(MP,4)*T(I,J+1,K) - C(MP,5)*T(I,J,K-1) -
              1 C(MP,6)*T(I,J,K+1))
ISN 0430      315 CONTINUE
ISN 0431      HDT = 0.0
ISN 0432      HDA = 0.0
ISN 0433      OTKNSP = 0.0
ISN 0434      DO 318 J=2,MM
ISN 0435      OSUM = 0.0
ISN 0436      DO 330 KK=1,N
ISN 0437      K = NNN - KK
ISN 0438      MP = MPAR(I,J,K)
ISN 0439      IF(C(MP,1).LE. 0.0) GO TO 330

```

ORIGINAL PAGE IS
OF POOR QUALITY

```

ISN 0441      IF (TIN(J,K) .GT. TVAP) GO TO 319
ISN 0443      HDT = HDT + HCON*TIN(J,K)*RIN*NPST(J)*DZ(K)
ISN 0444      HDA = HDA + HCON*RIN*NPST(J)*DZ(K)
ISN 0445      GO TO 330
ISN 0446      319 HDT = HDT + HEVP*TIN(J,K)*RIN*NPST(J)*DZ(K)
ISN 0447      HDA = HDA + HEVP*RIN*NPST(J)*DZ(K)
ISN 0448      OSUM = OSUM + HEVP*(TIN(J,K) - TVAP)*RIN*NPST(J)*DZ(K)
ISN 0449      IF (OSUM .GT. OMAXGR(J)) GO TO 331
ISN 0451      330 CONTINUE
ISN 0452      GO TO 332
ISN 0453      331 CONTINUE
C             IF OSUM IS LARGER THAN THE TRANSPORT LIMIT OF THE GROOVE, THE
C             GROOVE PARTIALLY DRIES OUT.
ISN 0454      K1 = K
ISN 0455      DO 335 K=2,NN
ISN 0456      IF (K .JJ. K1) GO TO 334
ISN 0458      C(IMP,1) = C1(I,J,K)
ISN 0459      GO TO 335
ISN 0460      334 C(IMP,1) = .1E-5
C             (FOR DRIED-OUT GROOVES C(IMP,1) IS SET EQUAL TO A SMALL NUMBER
C             FOR CONVENIENCE OF NUMERICAL ITERATION)
ISN 0461      335 CONTINUE

```

ORIGINAL PAGE 12
OF POOR QUALITY

```

ISN 0462      332 CONTINUE
ISN 0463      . DSINGL(J) = DSUM
ISN 0464      OTRNSP = OTRNSP + DSUM
ISN 0465      318 CONTINUE
ISN 0466      GO TO (311,312,312), KTYPE
ISN 0467      312 TVAP = H01/H0A
ISN 0468      TVAP = (1.0 - W)*TTVAP + W*TVAP
ISN 0469      I = 1
ISN 0470      DO 321 J=1,MM
ISN 0471      DO 321 K=1,NN
ISN 0472      T(I,J,K) = TVAP
ISN 0473      321 CONTINUE
ISN 0474      311 CONTINUE

C
ISN 0475      350 CONTINUE
C
C *****
C
C              CONVERGENCE CHECK
C
C *****
C
ISN 0476      DTMAX = ABS(TVAP-TTVAP)
ISN 0477      DO 360 K=2,NN
ISN 0478      DO 360 J=2,MM
ISN 0479      DO 360 I=2,LL
ISN 0480      DT = ABS(T(I,J,K)-TT(I,J,K))
ISN 0481      IF(DT .GT. DTMAX) DTMAX=DT
ISN 0483      360 CONTINUE
C
C      IS THIS MAXIMUM CHANGE ACCEPTABLE
C
ISN 0484      ITN = ITN + 1
ISN 0485      IF(DTMAX .GT. DTSPFC) GO TO 300
C
C      NUMBER OF ITERATION REQUIRED FOR CONVERGENCE
C
ISN 0487      NITN = (ITN - 1)*INIT
C
C *****
C
C              SURFACE TEMPERATURE CALCULATION
C
C *****
C
ISN 0488      I = LL
ISN 0489      DO 370 K=2,NN
ISN 0490      DO 370 J=2,MM
ISN 0491      MP = MPAR(I,J,K)
ISN 0492      C(MP,7) = C(MP,1) + C(MP,2) + C(MP,3) + C(MP,4) + C(MP,5) +
C(MP,6)
ISN 0493      CPRIME = C(MP,7) - C(MP,2) + C2(I,J,K)
ISN 0494      TOUT(I,J,K) = (1.0/C2(I,J,K))*[CPRIME*T(I,J,K) - C(MP,1)*T(I-1,J,K)
- C(MP,2)*T(I,J-1,K) - C(MP,4)*T(I,J+1,K) - C(MP,5)*T(I,J,K-1)
- C(MP,6)*T(I,J,K+1)]
ISN 0495      370 CONTINUE
C
C *****

```

ORIGINAL PAGE IS
OF POOR QUALITY

```
C
C  AVERAGE SURFACE TEMPERATURES OF EVAPORATOR AND CONDENSER
C
C  *****
C
ISN 0496      GO TO (371,372,373), KTYPE
ISN 0497      371 CONTINUE
C
C  FOR TYPE 1 BOUNDARY CONDITION
C
ISN 0498      TWFS = 0.0
ISN 0499      TWCS = 0.0
ISN 0500      DO 374 K=2,NN
ISN 0501      DO 374 J=2,MM
ISN 0502      IF (Z(K) .LT. XLF) TWFS=TWFS+THUT(J,K)*RPUT*DPST(J)*DZ(K)
ISN 0504      IF (Z(K) .GT. (XLF+XLAD)) TWCS=TWCS+THUT(J,K)*RPUT*(DPST(J)*DZ(K)
ISN 0506      374 CONTINUE
ISN 0507      TWFAV = TWFS/(2.*PA)*RPUT*XLF)
ISN 0508      TWCAV = TWCS/(2.*PA)*RPUT*XLCL)
ISN 0509      GO TO 375
C
ISN 0510      372 CONTINUE
```

ORIGINAL PAGE 75
OF POOR QUALITY

C FOR TYPE 2 BOUNDARY CONDITION

```

1SN 0511      TWCAV = TWC
1SN 0512      TWFS = 0.0
1SN 0513      DO 376 K=2,NN
1SN 0514      DO 376 J=2,MM
1SN 0515      IF (Z(K) .LT. XLF) TWFS=TWFS+TDUT(J,K)*ROUT*OPSI(J)*WZ(K)
1SN 0517      376 CONTINUE
1SN 0518      TWEAV = TWFS/(2.*PAI*ROUT*XLF)
1SN 0519      GO TO 375

```

15N 0520 373 CONTINUE

C. FOR TYPE 3 BOUNDARY CONDITION

ISN 0521	TWFAV = TW
ISN 0522	TWCAV = TW
ISN 0523	375 CONTINUE

EVAPORATOR AND CONDENSER OVERALL FILM COEFFICIENTS

ISN 0524 FILMFV = OTRNSP/(2.*PAI*RV*XL*(TWFAV - TVAP))
ISN 0525 FILMCD = OTRNSP/(2.*PAI*RV*XL*(TVAP - TWCAV))

```
C *****  
C  
C-----  
C          OUTPUT SECTION  
C-----  
C *****
```

```

1  ISN 0526      WRITE(6,961) JFIN
2  ISN 0527      961  FORMAT(' ',14X,'CASE NUMBER =',I2)
3  ISN 0528      WRITE(6,905)
4  ISN 0529      905  FORMAT(' ',15X,'HEAT PIPE OPERATING CONDITIONS')
5  ISN 0530      IF(MGRAV1.FO.1) GO TO 965
6  ISN 0532      WRITE(6,966)
7  ISN 0533      966  FORMAT(' ',20X,'ONE-G CONDITION')
8  ISN 0534      GO TO 967
9  ISN 0535      965  WRITE(6,968)
10 ISN 0536      968  FORMAT(' ',20X,'ZER-G CONDITION')
11 ISN 0537      967  CONTINUE
12 ISN 0538      GO TO (906,907,908), KTYPE
13 ISN 0539      906  WRITE(6,909) Q10TL,TVAP
14 ISN 0540      909  FORMAT(20X,'TYPE 1 MANDIARY CONDITION'//
15                  1  20X,'TOTAL HEAT INPUT(W)',I67,F15.2/
16                  1  20X,'VAPOR TEMPERATURE(K)',I67,F15.2)
17 ISN 0541      GO TO 950

```

ISN 0541	GO TO 950	20X, 'VAPOR TEMPERATURE(K)', T67, F15.2)
ISN 0542	907 WRITE(6,910) C101L, TW.	
ISN 0543	910 FORKMA(1(20X, 'TYPE 2 SECONDARY CONDITION //	
	1	20X, 'TOTAL HEAT INPUT(W)', T67, F15.2/
	1	20X, 'CONDENSER WALL TEMPERATURE(K)', T67, F15.2)
ISN 0544	GO TO 950	

ORIGINAL PAGE 13
OF FOUR PAGES

ISN 0545	908	WRITE(6,911) TWF,TWC
ISN 0546	911	FORMAT(20X,'TYPE 3 BOUNDARY CONDITION'//
	1	20X,'EVAPORATOR WALL TEMPERATURE(K)',T67,F15.2/
	1	20X,'CONDENSER WALL TEMPERATURE(K)',T67,F15.2)
ISN 0547		WRITE(6,958) OMAX(IIRIN)
ISN 0548	958	FORMAT(20X,'MAX. HEAT TRANSPORT UNDER O-G(W)',T67,F15.2)
ISN 0549	950	CONTINUE
ISN 0550		WRITE(6,912) TEMP,HPAR
ISN 0551	912	FORMAT(20X,'AMBIENT TEMPERATURE(K)',T67,F15.2/
	1	20X,'HEAT TRANSFER COEFF. FOR PARASITIC'//
	1	20X,'HEAT LOSS OR GAIN(W/(M**2*K))',T70,F15.5)
ISN 0552		IF(MGRAV1.EQ.1) GO TO 969
ISN 0554		WRITE(6,970) XSMAS,FLV,XSTHT
ISN 0555	970	FORMAT(20X,'EXCESS MASS CHARGE(KG)',T70,F15.5/
	1	20X,'ELEVATION(M)',T70,F15.5/
	1	20X,'STATIC HEIGHT OF PIPE(M)',T70,F15.5)
ISN 0556	969	CONTINUE
ISN 0557		WRITE(6,904) RHOL,CONL,CONW
ISN 0558	904	FORMAT(//,15X,'PROPERTIES OF WORKING FLUID AND PIPE MATERIAL'//,
	1	20X,'FLUID DENSITY(KG/M**3)',T70,F15.5/
	1	20X,'FLUID THERMAL CONDUCTIVITY(W/(M*K))',T70,F15.5/
	1	20X,'WALL THERMAL CONDUCTIVITY(W/(M*K))',T70,F15.5)

ORIGINAL PAGE IS
OF POOR QUALITY

```

ISN 0559      WRITE(6,913)
ISN 0560      913 FORMAT(////,25X,'SURFACE TEMPERATURE DISTRIBUTION (DEGREES K)')
ISN 0561      WRITE(6,914)
ISN 0562      914 FORMAT(2X,'AXIAL',30X,'CIRCUMFERENTIAL LOCATION')
ISN 0563      WRITE(6,930)
ISN 0564      930 FORMAT(1X,'LOCATION')
ISN 0565      WRITE(6,931)
ISN 0566      931 FORMAT(3X,'Z (M)',25X,'PSI (DEGREES)')
ISN 0567      DO 951 J=1,MM
ISN 0568      DEGPSI(J) = PSI(J)*180.0/PAI
ISN 0569      951 CONTINUE
ISN 0570      WRI C(6,915) (DEGPSI(J),J=2,MM,3)
ISN 0571      915 FORMAT(10X,12F9.1)
ISN 0572      WRITE(6,932)
ISN 0573      932 FORMAT( )
ISN 0574      DO 952 K=2,NN,2
ISN 0575      WRITE(6,916) Z(K),(TOUT(J,K),J=2,MM,3)
ISN 0576      916 FORMAT(F7.3,3X,12F9.2)
ISN 0577      952 CONTINUE
ISN 0578      WRITE(6,987)
ISN 0579      987 FORMAT(11,35X,'HEAT TRANSPORT OF EACH GROOVE')
ISN 0580      WRITE(6,988) (J,J=1,12)
ISN 0581      WRITE(6,989) (OSINGL(J),J=2,13)
ISN 0582      WRITE(6,988) (J,J=13,24)
ISN 0583      WRITE(6,989) (OSINGL(J),J=14,25)
ISN 0584      WRITE(6,988) (J,J=25,M)
ISN 0585      WRITE(6,989) (OSINGL(J),J=26,MM)
ISN 0586      988 FORMAT(//,2X,'GROOVE NO.',6X,12I8)
ISN 0587      989 FORMAT(//,2X,'HEAT TRANSPORT (W)',12F8.3)
ISN 0588      WRITE(6,917)
ISN 0589      917 FORMAT(///,30X,'HEAT PIPE PERFORMANCE CHARACTERISTICS',//)
ISN 0590      DTEVAP = TWFAV - TWCAV
ISN 0591      DTCOND = TVAP - TWCAV
ISN 0592      WRITE(6,918) QTRNSP,QMAXHP,TVAP,TWFAV,TWCAV,DTEVAP,DTCOND,
1      FILMFV,FILMCN
ISN 0593      918 FORMAT(20X,'TOTAL HEAT TRANSPORT(W)',T70,F15.2/
1      20X,'MAXIMUM HEAT TRANSPORT(W)',T70,F15.2/
1      20X,'VAPOR TEMPERATURE(K)',T70,F15.2//
1      20X,'AVERAGE EVAP. SURFACE TEMP.(K)',T70,F15.2/
1      20X,'AVERAGE COND. SURFACE TEMP.(K)',T70,F15.2//
1      20X,'AVERAGE EVAP. TEMPERATURE DROP(K)',T70,F15.2/
1      20X,'AVERAGE COND. TEMPERATURE DROP(K)',T70,F15.2//
1      20X,'EVAPORATOR FILM COEFFICIENT(W/(M**2*K)',T70,F15.4/
1      20X,'CONDENSER FILM COEFFICIENT(W/(M**2*K)',T70,F15.4)
ISN 0594      IF(MGRAV1.EQ.1) GO TO 945
ISN 0596      IF(1/PUDL.EQ.1) GO TO 946
ISN 0598      WRITE(6,947)
ISN 0599      947 FORMAT(//,20X,'PUDDLE EFFECT IS INCLUDED')
ISN 0600      GO TO 945
ISN 0601      946 WRITE(6,948)
ISN 0602      948 FORMAT(//,20X,'PUDDLE EFFECT IS NOT INCLUDED')
ISN 0603      945 CONTINUE
ISN 0604      DO 953 J=2,MM
ISN 0605      IF(OSINGL(J).GT.(QMAXGR(J))) GO TO 954
ISN 0607      953 CONTINUE
ISN 0608      WRITE(6,955)
ISN 0609      955 FORMAT(//,20X,'NO PARTIAL DRY-OUT IS EXPECTED')
ISN 0610      GO TO 956

```

ORIGINAL PAGE 13
OF POOR QUALITY

```
ISN 0611      954 WRITE(6,957)
ISN 0612      957 FORMAT(//,20X,'PARTIAL DRY-OUT IS EXPECTED')
ISN 0613      956 CONTINUE
ISN 0614      WRITE(6,971) NITN
ISN 0615      971 FORMAT(//,20X,'INITIAL NUMBER OF ITERATIONS REQUIRED =',I5)
ISN 0616      GO TO 50
               C
ISN 0617      973 CONTINUE
ISN 0618      WRITE(6,961) IRIN
ISN 0619      WRITE(6,975)
ISN 0620      975 FORMAT(//,20X,'INITIAL HEAT INPUT EXCEEDS HEAT TRANSPORT LIMIT ')
               C
               C
ISN 0621      50 CONTINUE
ISN 0622      STOP
ISN 0623      END
```


ORIGINAL PAGE IS
OF POOR QUALITY

05/260 HIRTRAN H

COMPILER OPTIONS - NAME= MAIN,OPT=02,TIMECN1=R2,SIZE=0000K,
SOURCE,PRCDIC,NOLISJ,MODECK,LOAD,MAP,MODED11,1D,XRFF

ISN 0002

SUBROUTINE PUDDLE

C

C THIS SUBROUTINE DETERMINES THE REGION COVERED BY A LIQUID POOL AND

C IMPOSES CONDITION THAT HEAT TRANSFER RATE IS ZERO OVER THE REGION

C THIS PROGRAM ALSO CALCULATES CHANGE OF MAX. HEAT TRANSFER DUE TO

C PUDDLE FOR EACH GROOVE

C

ISN 0003

DIMENSION C(4000,R),Z(32),OMAXGR(35),XPDL(35),XIKNS(35)

ISN 0004

COMMON C,7,XLF,XLAD,XLC,XL,RV,NGRV,XSTHT,L,M,MM,N,NN,NNN,

RHNL,XSMAS,FLV,OMXO,OMAXGR

C

C

ISN 0005

MPAR(I,J,K) = (K-1)*L*M + (J-1)*M + J

ISN 0006

PAI = 3.14159

C

ISN 0007

DO 740 J=2,MM

ISN 0008

XPDI(J) = 0.0

ISN 0009

740 CONTINUE

ISN 0010

XSVOL = XSMAS/RHNL

C

C

C CLASSIFY PUDDLE SHAPE

C

ISN 0011

XH1 = 2.0*XSVOL/((PAI*RV*XL) + .5*FLV

ISN 0012

XH0 = XH1 - FLV

ISN 0013

IF(FLV.GT.(2.0*RV)) GO TO 703

ISN 0015

IF(XH0.LE.0.0) GO TO 710

ISN 0017

IF(XH1.GT.(2.0*RV)) GO TO 711

ISN 0019

GO TO 712

ISN 0020

703 CONTINUE

ISN 0021

IF(XH1.LE.(2.0*RV)) GO TO 710

ISN 0023

IF(XH0.GT.0.0) GO TO 711

ISN 0025

GO TO 713

C

ISN 0026

710 CONTINUE

C

C

C PUDDLE SHAPE

C

ISN 0027

XH1 = 2.0*RV*SQRT(XSVOL*FLV/((PAI*XL*(RV)**3))

ISN 0028

XLP = XH1*XL/FLV

ISN 0029

I = 2

ISN 0030

DO 720 KK=1,N

ISN 0031

K = NNN - KK

ISN 0032

DO 720 J=2,MM

ISN 0033

MP = MPAR(I,J,K)

ISN 0034

ZHC = XL - Z(K)

ISN 0035

IF(ZHC.GT.XLP) GO TO 721

ISN 0037

HGP = 1.0 - XH1/RV + ZHC*FLV/(RV*XL)

ISN 0038

IF(HGP.GT.1.0) HGP=1.0

ISN 0040

PANGL = ARCCOS(HGP)

ISN 0041

JPIID = PANGL*NGRV/(2.*PAI)

ISN 0042

IF(J.GT.(JPIID+1).AND.J.LE.(MM-JPIID+1)) GO TO 720

ISN 0044

C(MP,I) = 0.0

ISN 0045

XPDI(J) = ZHC

ISN 0046

720 CONTINUE

ISN 0047

721 CONTINUE

ISN 0048

GO TO 750

ORIGINAL PAGE IS
OF POOR QUALITY

ISN 0049	C	711 CONTINUE
	C	
	C	RIDDLE SHAPE 2
	C	
ISN 0050		$XLPI = XL - \text{SORT}(4.0 * XL * (PAI * XL * (RV)^2 - XSMI) / (PAI * RV * FLV))$
ISN 0051		$XHO = 2.0 * RV - (XL - XLPI) * FLV / XL$
ISN 0052		$I = ?$
ISN 0053		DO 725 KK=1,N
ISN 0054		$K = NNM - KK$
ISN 0055		DO 725 J=2,MM
ISN 0056		$MP = \text{MPAR}(I, J, K)$
ISN 0057		$ZHC = XL - Z(K)$
ISN 0058		IF (ZHC .GT. XLPI) GO TO 726
ISN 0060		$C(MP, I) = 0.0$
ISN 0061	726	CONTINUE
ISN 0062		$PANGL = \text{ARCOS}((ZHC - XLPI) * FLV / (RV * XL) - 1.0)$
ISN 0063		$JPIID = PANGL * NGRV / (2. * PAI)$
ISN 0064		IF (J .GT. (JPIID+1) .AND. J .LT. (MM-JPIID+1)) GO TO 725
ISN 0066		$C(MP, I) = 0.0$
ISN 0067		$XPDL(J) = ZHC$
ISN 0068	725	CONTINUE

ORIGINAL PAGE IS
OF POOR QUALITY

```

ISN 0069      GO TO 750
C
ISN 0070      712 CONTINUE
C
C , PIDDLE SHAPE 3
C
ISN 0071      XH1 = 2.0*XSVDL/(PA1*RV*XL) + .5*FLV
ISN 0072      I = 2
ISN 0073      DO 730 KK=1,N
ISN 0074      K = NNN - KK
ISN 0075      DO 730 J=2,MM
ISN 0076      MP = MPAR(I,J,K)
ISN 0077      ZHC = XL - Z(K)
ISN 0078      PANG1 = ARCOS(1.0 - XH1/RV + ZHC*FLV/(RV*XL))
ISN 0079      JPU1 = PANG1*NGRV/(2.*PA1)
ISN 0080      IF(J.GT.(JPU1+1)).AND.J.LT.(MM-JPU1+1)) GO TO 730
ISN 0081      C(MP,1) = 0.0
ISN 0082      XPDL(J) = ZHC
ISN 0083      730 CONTINUE
ISN 0084      GO TO 750
C
ISN 0085      713 CONTINUE
C
C , PIDDLE SHAPE 4
C
ISN 0087      XLP1 = XL - SQRT(4.0*XL*(PA1*XL*(RV)**2 - XSVDL)/(PA1*RV*FLV))
ISN 0088      XLP = XLP1 + 2.0*RV*XL/FLV
ISN 0089      I = 2
ISN 0090      DO 735 KK=1,N
ISN 0091      K = NNN - KK
ISN 0092      DO 735 J=2,MM
ISN 0093      MP = MPAR(I,J,K)
ISN 0094      ZHC = XL - Z(K)
ISN 0095      IF(ZHC.GT.XLP1) GO TO 736
ISN 0096      C(MP,1) = 0.0
ISN 0097      736 CONTINUE
ISN 0098      IF(ZHC.GT.XLP) GO TO 737
ISN 0099      PANG1 = ARCOS((ZHC - XLP1)*FLV/(RV*XL) - 1.0)
ISN 0100      JPU1 = PANG1*NGRV/(2.*PA1)
ISN 0101      IF(J.GT.(JPU1+1)).AND.J.LT.(MM-JPU1+1)) GO TO 735
ISN 0102      C(MP,1) = 0.0
ISN 0103      XPDL(J) = ZHC
ISN 0104      735 CONTINUE
ISN 0105      737 CONTINUE
C
ISN 0106      750 CONTINUE
C
ISN 0110      DO 741 J=2,MM
ISN 0111      IF(XPDL(J).GT.XLC) GO TO 742
ISN 0112      XTRNS(J) = .5*XLF + XLAD + .5*(XLC - XPDL(J))
ISN 0113      GO TO 743
ISN 0114      742 IF(XPDL(J).GT.(XLC+XLAD)) GO TO 744
ISN 0115      XTRNS(J) = .5*XLF + (XLC + XLAD - XPDL(J))
ISN 0116      GO TO 743
ISN 0117      744 XTRNS(J) = .5*(XL - XPDL(J))
ISN 0118      743 CONTINUE
ISN 0119      XTRNS0 = .5*XLF + XLAD + .5*XLC
ISN 0120      QMAXGR(J) = QMX0*(XTRNS0/XTRNS(J))*(1.0 - (FLV/XSTHT))*

```

ORIGINAL PAGE IS
OF POOR QUALITY

ISN 0123

1 (1.0 - XPDL (J)/XL))

741 CONTINUE

C

ISN 0124

RETURN

ISN 0125

END

(

ORIGINAL PAGE IS
OF POOR QUALITY

APPENDIX C

SAMPLE OUTPUT

(

 THERMAL ANALYSIS OF AXIALLY GROOVED HEAT PIPE

NAMES OF WORKING FLUID AND PIPE MATERIAL

WORKING FLUID
 PIPE MATERIAL

AMMONIA
 ALUMINUM

HEAT PIPE DIMENSIONS

EVAPORATOR LENGTH(M)	0.30480E+00
ADIABATIC LENGTH(M)	0.45720E+00
CONDENSER LENGTH(M)	0.15240E+00
TOTAL PIPE LENGTH(M)	0.91440E+00
PIPE OUTER DIAMETER(M)	0.15900E+01
PIPE INNER DIAMETER(M)	0.10880E+01
VAPOR CORE RADIUS(M)	0.45000E+02

GROOVE DIMENSIONS

NUMBER OF GROOVES	27
GROOVE DEPTH(M)	0.10800E+02
AVERAGE LAND WIDTH(M)	0.37000E+03

HEATING AND COOLING MODES

EVAPORATOR REGION	NON-UNIFORM HEATING HEATING REGION COVERS FROM PSI= 90.0 DEG TO PSI=270.0 DEG
CONDENSER REGION	NON-UNIFORM COOLING COOLING REGION COVERS FROM PSI= 0.0 DEG TO PSI= 90.0 DEG AND FROM PSI=270.0 DEG TO PSI=360.0 DEG

ORIGINAL SPEC IS
 OF POOR QUALITY

CASE NUMBER = 1

HEAT PIPE OPERATING CONDITIONS

ONE-G CONDITION
TYPE 1 BOUNDARY CONDITION

TOTAL HEAT INPUT(W)	80.00
VAPOR TEMPERATURE(K)	250.00
AMBIENT TEMPERATURE(K)	0.0
HEAT TRANSFER COEFF. FOR PARASITIC HEAT LOSS OR GAIN(W/(M**2*K))	0.0
EXCESS MASS CHARGE(KG)	0.12000E-02
ELEVATION(M)	0.60000E-02
STATIC HEIGHT OF PIPE(M)	0.14000E-01

PROPERTIES OF WORKING FLUID AND PIPE MATERIAL

FLUID DENSITY(KG/M**3)	0.67000E 03
FLUID THERMAL CONDUCTIVITY(W/(M*K))	0.59200E 00
WALL THERMAL CONDUCTIVITY(W/(M*K))	0.18000E 03

SURFACE TEMPERATURE DISTRIBUTION (DEGREES K)

AXIAL LOCATION Z (M)	CIRCUMFERENTIAL LOCATION PSI (DEGREES)								
----------------------------	---	--	--	--	--	--	--	--	--

	0.7	40.7	80.7	120.7	160.7	200.7	240.7	280.7	320.7
0.015	250.77	250.95	251.44	251.80	251.93	251.87	251.60	251.07	250.81
0.076	250.78	250.96	251.45	251.81	251.94	251.88	251.62	251.08	250.82
0.137	250.78	250.96	251.45	251.81	251.94	251.88	251.62	251.08	250.82
0.198	250.78	250.96	251.45	251.81	251.94	251.88	251.62	251.08	250.82
0.259	250.78	250.95	251.45	251.81	251.94	251.88	251.61	251.08	250.82
0.351	250.02	250.02	250.02	250.03	250.03	250.03	250.03	250.02	250.02
0.533	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00	250.00
0.716	249.98	249.99	249.99	250.00	250.00	250.00	249.99	249.99	249.99
0.785	246.81	247.61	248.76	249.42	249.63	249.55	249.11	248.06	247.22
0.815	246.18	247.12	248.56	249.33	249.58	249.49	249.01	247.79	246.60
0.846	246.17	247.11	248.55	249.33	249.58	249.49	249.00	247.78	246.59
0.876	246.17	247.11	248.55	249.33	249.58	249.49	249.00	247.78	246.59
0.907	246.17	247.11	248.55	249.33	249.58	249.49	249.00	247.78	246.59

ORIGINAL PAGE IS
OF POOR QUALITY

HEAT TRANSPORT OF EACH GROOVE

GROOVE NO.	1	2	3	4	5	6	7	8	9	10	11	12
HEAT TRANSPORT (W)	1.713	1.785	1.911	2.094	2.340	2.652	3.015	3.331	3.585	3.781	3.924	4.018
GROOVE NO.	13	14	15	16	17	18	19	20	21	22	23	24
HEAT TRANSPORT (W)	4.067	4.069	4.027	3.939	3.800	3.608	3.356	3.042	2.676	2.364	2.115	1.927
GROOVE NO.	25	26	27									
HEAT TRANSPORT (W)	1.796	1.718	1.690									

HEAT PIPE PERFORMANCE CHARACTERISTICS

TOTAL HEAT TRANSPORT(W)	78.34
MAXIMUM HEAT TRANSPORT(W)	132.15
VAPOR TEMPERATURE(K)	250.00
AVERAGE EVAP. SURFACE TEMP.(K)	251.36
AVERAGE COND. SURFACE TEMP.(K)	248.23
AVERAGE EVAP. TEMPERATURE DROP(K)	1.36
AVERAGE COND. TEMPERATURE DROP(K)	1.77
EVAPORATOR FILM COEFFICIENT(W/(M**2*K))	0.6701E 04
CONDENSER FILM COEFFICIENT(W/(M**2*K))	0.1028E 05
PUDDLE EFFECT IS INCLUDED	
NO PARTIAL DRY-OUT IS EXPECTED	
TOTAL NUMBER OF ITERATIONS REQUIRED = 55	

Page 15
OF POOR QUALITY